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Timothy H. Cox and Alisa Marshall
NASA Dryden Flight Research Center
Edwards, California

May 2000

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National Aeronautics and
Space Administration

Dryden Flight Research Center
Edwards, California 93523-0273

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ABSTRACT

Four flights have been conducted using the Tu-144LL supersonic transport aircraft with the dedicated objective of collecting quantitative data and qualitative pilot comments. These data are compared with the following longitudinal flying qualities criteria: Neal-Smith, short-period damping, time delay, control anticipation parameter, phase delay ($\omega_{sp} * T_{\theta_2}$), pitch bandwidth as a function of time delay, and flightpath as a function of pitch bandwidth. Determining the applicability of these criteria and gaining insight into the flying qualities of a large, supersonic aircraft are attempted. Where appropriate, YF-12, XB-70, and SR-71 pilot ratings are compared with the Tu-144LL results to aid in the interpretation of the Tu-144LL data and to gain insight into the application of criteria. The data show that approach and landing requirements appear to be applicable to the precision flightpath control required for up-and-away flight of large, supersonic aircraft. The Neal-Smith, control anticipation parameter, and pitch-bandwidth criteria tend to correlate with the pilot comments better than the phase delay criterion, $\omega_{sp} * T_{\theta_2}$. The data indicate that the detrimental flying qualities implication of decoupled pitch-attitude and flightpath responses occurring for high-speed flight may be mitigated by requiring the pilot to close the loop on flightpath or vertical speed.

NOMENCLATURE

CAP	control anticipation parameter, $g^{-1}\ \mathrm{sec}^{-2}$
dt	time step interval, sec
g	acceleration caused by gravity
h	altitude
$\dot{h}$	altitude rate
ITB	integrated test block
m.s.l.	mean sea level
Nz	normal acceleration, g
PID	parameter identification
s	Laplace operator
T_{θ_2}	high-frequency pitch-attitude time constant, rad/sec
V	true airspeed
VRI	vertical regime indicator
γ	flightpath angle, rad
$\dot{\gamma}$	flightpath angle rate, rad/sec
$\phi_{2\omega_{180°}}$	phase angle at twice the phase crossover frequency, rad/sec
θ	pitch attitude, deg
θ_c	pitch-attitude command, deg

τ_p bandwidth phase delay parameter, sec

ω_{sp} short-period frequency, rad/sec

$\omega_{sp}*T_{\theta_2}$ phase delay, rad

$\omega_{180°}$ phase crossover frequency, rad/sec

INTRODUCTION

Most flying qualities criteria primarily have been developed from data in the low-angle-of-attack, subsonic regime. Unique characteristics of supersonic flight raise questions on whether these criteria successfully extend into the supersonic flight regime. This report describes an experiment to add to the database to answer these questions.

During the 1960's, the Tupolev Aircraft Company (Moscow, Russia) of the former Union of Soviet Socialist Republics designed and built the Tu-144 supersonic passenger aircraft to compete with the Concorde aircraft built by the French and British. Although the Tu-144 aircraft became the first supersonic passenger aircraft in the world to fly (in December of 1968), its technology never matured enough to become successful in passenger service. During the 1980's, the Tu-144 program was discontinued and the 19 aircraft that had been manufactured were either abandoned or used as research aircraft test beds. In 1994, Tupolev, funded by NASA, refurbished, instrumented, and refitted with new engine types the second-to-the-last-manufactured Tu-144 aircraft to support the NASA High-Speed Research program.

This modified airplane, redesignated the Tu-144LL aircraft, flew 19 flights from November 1996 to February 1998. Data were acquired for six flight experiments, including a handling qualities experiment. One prime objective of the handling qualities experiment was to collect data to validate handling qualities criteria being used in the design of the High-Speed Civil Transport. Only quantitative handling qualities data were collected during this program, not pilot opinions, comments, or ratings. A second phase of the program consisting of eight additional flights was conducted, including three flights flown by two NASA pilots for the purpose of evaluating the aircraft handling qualities. In September 1998, the three handling qualities flights were completed. Reference 1 documents the results from these evaluations and the experience of the U. S. team in conducting flight test with Tupolev at Zhukovsky airfield (near Moscow, Russia).

Some of the quantitative and qualitative data generated from this program previously has been analyzed and will be presented in a report by Morelli pending from the NASA Langley Research Center (Hampton, Virginia). The pending report will document estimation of parameters such as short-period frequency (ω_{sp}), high-frequency pitch-attitude time constant (T_{θ_2}), short-period damping, time delay, and other classical handling qualities parameters, including lateral-directional parameters. The report also will compare data with military standard criteria for both the up-and-away and terminal phase of flight.

This report does not attempt to duplicate the analysis in the Morelli report but rather to build on it. In addition, this report evaluates the Tu-144LL data with other criteria such as Neal-Smith, bandwidth, and flightpath bandwidth. The validity of these criteria is assessed, thereby gaining insight into the flying qualities of large, supersonic aircraft. Where appropriate, comparisons with YF-12, XB-70 and SR-71

data are made to aid in the interpretation of Tu-144LL data and to gain further insight into the application of the criteria. This report is limited to discussion of the longitudinal axis in up-and-away flight and does not include approach and landing characteristics.

AIRCRAFT DESCRIPTION

The Tu-144 aircraft (fig. 1), which cruises at a speed of Mach 2, is a delta-wing aircraft similar in size and weight to the Concorde aircraft (fig. 2). Like the Concorde aircraft, the Tu-144 nose droops in the approach-and-landing configuration to increase the pilot's field of view. Unlike the Concorde aircraft, the Tu-144 design incorporates a retractable canard that is deployed to allow slower approach and touchdown speeds. Through funding from the NASA High-Speed Research program, a Tu-144 "D" model airplane was refitted with four NK-321 engines (Samara Scientific and Technical Complex named after N. D. Kuznetsov, Samara, Russia) and redesignated the Tu-144LL flying laboratory airplane (fig. 3). Table 1 shows some Tu-144LL and Concorde characteristics.

The Tu-144LL airplane incorporates a conventional wheel and column and conventional rudder pedals for pilot interface; rate feedbacks are added for damping. Turn coordination is aided at speeds between Mach 0.9 and Mach 1.6 by an aileron-to-rudder interconnect. At speeds faster than Mach 1.6, sideslip feedback is added for stability augmentation. Two instruments in the cockpit are useful to the piloting task (fig. 4). One is a vertical regime indicator (VRI), which displays the aircraft altitude and airspeed with the profiles for the climb to and descent from cruise flight overplotted. The other is a pitch-attitude ladder displaying 0.5° increments. The aircraft has an autopilot, including autothrottle, that is used only in the landing pattern.
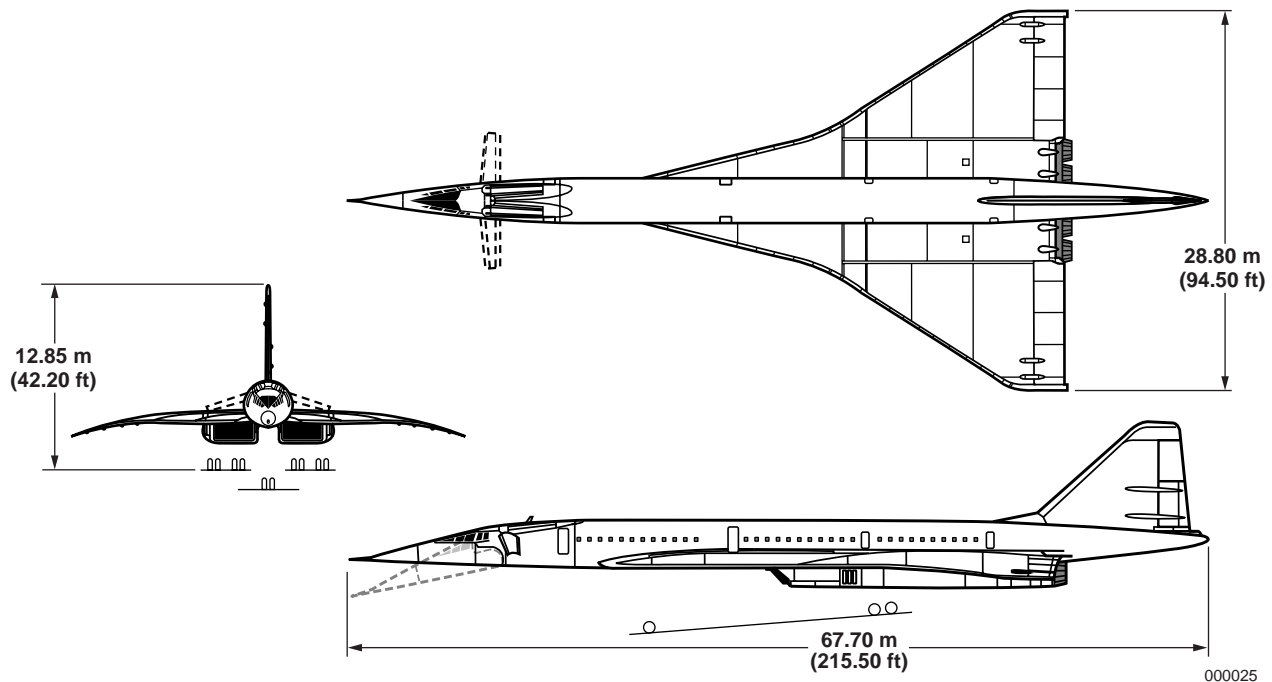

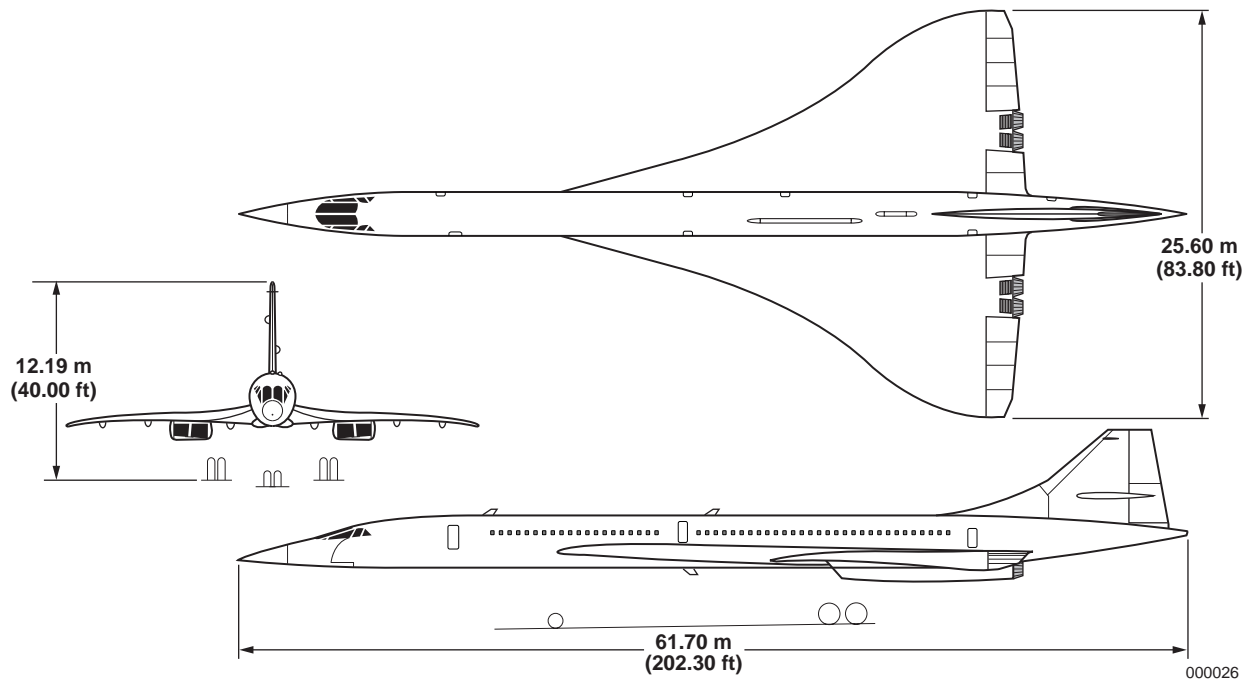Figure 1. Three-view drawing of the Tu-144 production supersonic passenger aircraft.

Figure 2. Three-view drawing of the Concorde aircraft.

12.19 m
(40.00 ft)

25.60 m
(83.80 ft)

61.70 m
(202.30 ft)

000026

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Figure 3. Photograph of the Tu-144LL airplane in the cruise configuration.

Table 1. Tu-144LL and Concorde aircraft characteristics.

| Characteristic	Tu-144LL airplane	Concorde aircraft
Length	65.7 m (215.5 ft)	61.7 m (202.3 ft)
Wingspan	28.8 m (94.5 ft)	25.6 m (83.8 ft)
Maximum takeoff weight	203,000 kg (447,500 lb)	176,445 kg (389,000 lb)
Maximum fuel capacity	95,000 kg (209,440 lb)	$\approx$ 84,365 kg (186,000 lb)
Estimated range	3000 km (1620 nmi)	6380 km (3450 nmi)
Maximum ceiling	19,000 m (62,335 ft)	20,725 m (68,000 ft)
Maximum Mach number	2.40	2.17
Maximum static thrust for each engine	24,950 kg (55,000 lbf)	17,260 kg (38,050 lbf)
Wing area	438.0 m^2 (4714.5 ft^2)	358.3 m^2 (3856.0 ft^2)
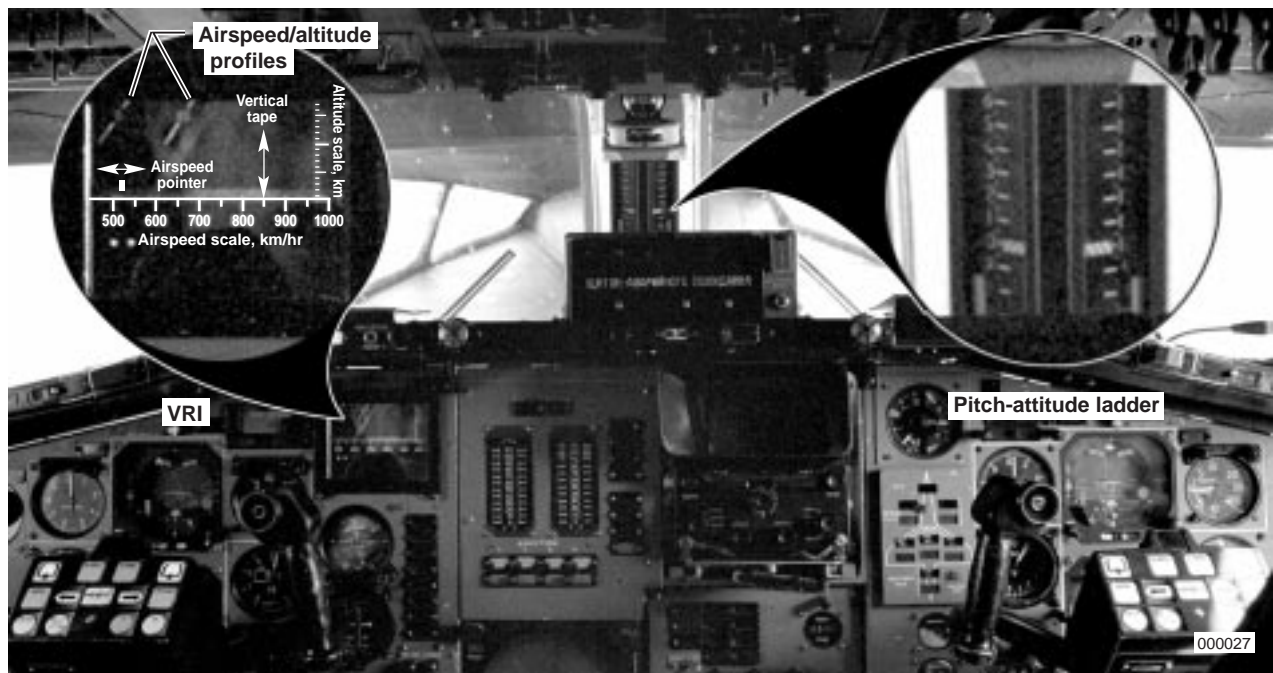
Figure 4. Cockpit of the Tu-144LL airplane with pitch-attitude ladder and VRI identified.

DESCRIPTIONS OF OTHER LARGE, SUPERSONIC AIRCRAFT USED IN ANALYSIS

Approximately 30 years ago, flight research programs were conducted for XB-70 and YF-12 aircraft at the NASA Dryden Flight Research Center (Edwards, California). To supplement the data from these programs, a research program using the SR-71 airplane was conducted approximately seven years ago. Where appropriate, handling qualities flight data from these YF-12, XB-70, and SR-71 programs have been used to add insight into the Tu-144LL analysis.

The following subsections provide a brief description for each of these other aircraft. References 2 and 3 provide information concerning the XB-70 and YF-12 research programs, respectively.

XB-70 Aircraft

The XB-70 aircraft was a delta-wing aircraft designed for Mach-3 cruise flight. Two airplanes were built, designated the XB-70-1 and the XB-70-2 (fig. 5). The XB-70-1 wing had 0° of geometric dihedral; the XB-70-2 wing had 5° of dihedral. The two airplanes were similar in all other respects.
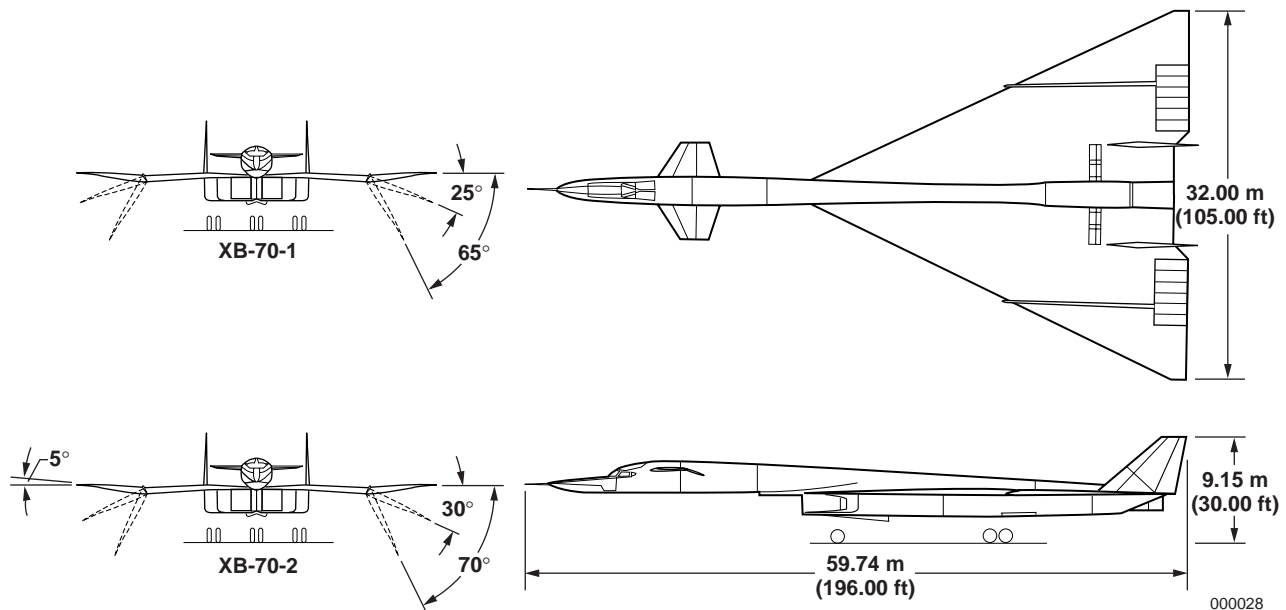

Figure 5. Three-view drawing of the XB-70 aircraft.

Both airplanes had movable wing tips for improved directional stability at high speeds. For low speeds, the wing tips were undeflected; for subsonic and transonic speeds, the wing tips were deflected 25° down from the wing line; and for supersonic speeds, the wing tips were deflected 65° down from the wing line. The nose was lowered in subsonic flight to increase the pilot's field of view. Elevons and a canard provided longitudinal control; two vertical stabilizers provided directional control; and differential movement of the elevons provided lateral control. Both airplanes had a stability augmentation system for the pitch, roll, and yaw axes. The overall system reduced variations in stick force/g as flight condition changed.

YF-12 Aircraft

The YF-12 aircraft was a twin-engine, delta-wing aircraft designed for long-range cruise flight at speeds faster than Mach 3.0 and altitudes higher than 22,000 m (72,000 ft). Figure 6 shows a three-view drawing of the aircraft used for the analysis in this report, the YF-12C airplane.
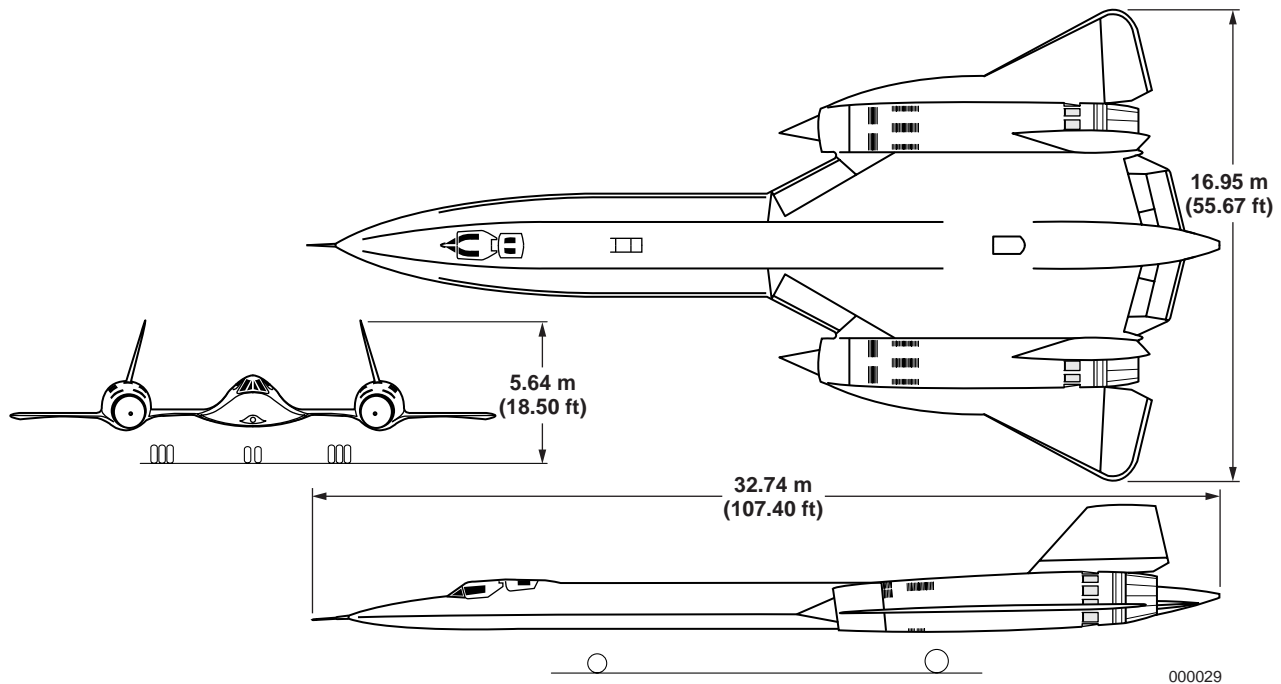

Figure 6. Three-view drawing of the YF-12C aircraft.

Two elevons on each wing, one inboard and one outboard of the engine nacelle, performed the combined functions of ailerons and elevons. Two all-movable, vertical tails provided directional stability and control. The airplane normally used a stability augmentation system to provide artificial stability and damping in the pitch and yaw axes. The system also enhanced roll damping.

SR-71 Aircraft

Nearly identical to the YF-12 aircraft used in this study, the SR-71 aircraft is a twin-engine, delta-wing aircraft designed to cruise at a speed of Mach 3.2 to altitudes higher than 24,400 m (80,000 ft). Wing trailing-edge elevons are used symmetrically as elevators and differentially as ailerons to provide longitudinal and lateral control. Two all-movable, vertical tails supply directional control.

The pilot controls consist of a conventional stick for pitch and roll inputs and conventional rudder pedals for yaw inputs. The SR-71 aircraft has a conventional response in that angle-of-attack and normal acceleration changes are commanded by the pitch stick. The aircraft also has an automatic flight control system that provides stability augmentation in the pitch and yaw axes and increased damping in all three axes using conventional feedback of roll, pitch, and yaw rates. In addition, lateral acceleration feedback is used in the yaw axis.

THE HANDLING QUALITIES EVALUATION PROGRAM

The first of the four Tu-144LL handling qualities evaluation flights, designated flight 20, was flown by an all-Russian crew. This flight was a functional check after an extended downtime for the aircraft.

The American pilot evaluation team (consisting of two pilots and three engineers) reached a consensus on the highest priorities for the remaining three flights, deciding that both American pilots would evaluate the Mach-2 flight regime and still allow for several evaluations of the approach-and-landing characteristics. Flight 21 was restricted to the subsonic regime. This flight, flown by pilot A, concentrated on evaluating takeoff and approach configurations of the airplane and subsonic cruise flight at Mach 0.9. Flights 22 and 23 were flown by pilot B and pilot A, respectively, with approximately 20 min at a speed of Mach 2.0 for each. Figure 7 shows the flight profile for flight 22. Each flight is detailed in reference 1, as is an overview of the experience of conducting flight test with Tupolev.
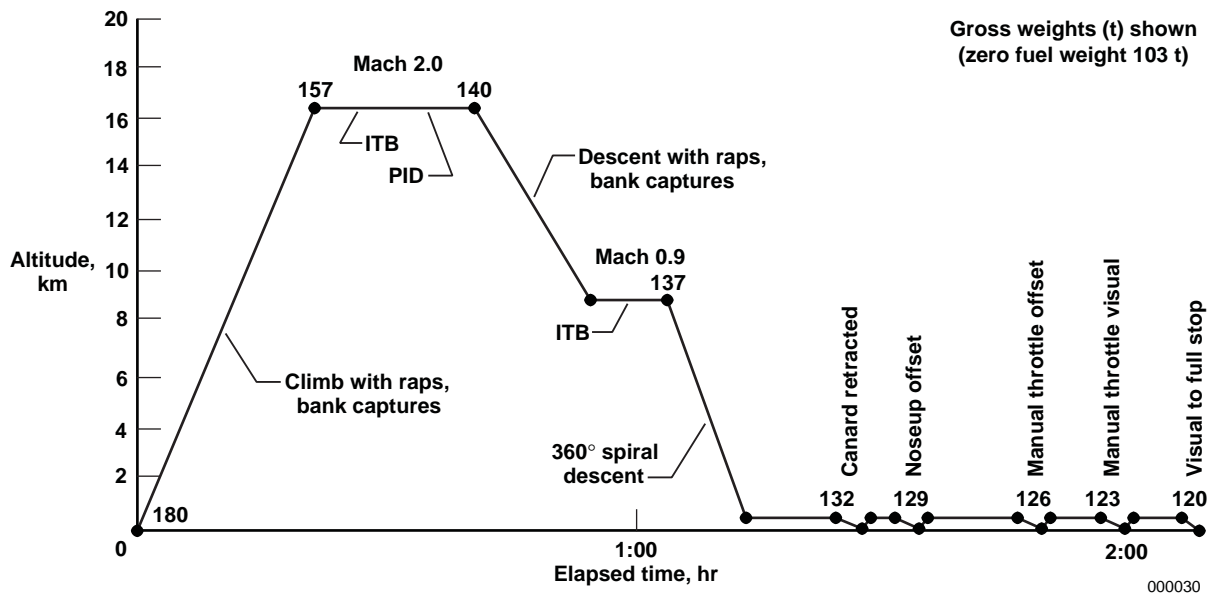

Figure 7. Flight profile of flight 22.

Task Description and Configurations

To aid the evaluations, specifically defined maneuvers were established and repeated for different flight conditions and aircraft configurations. A standard block of maneuvers, designated an integrated test block (ITB), was designed to provide a consistent evaluation of the airplane. The maneuvers consisted of pitch-attitude, bank-angle, and heading captures; steady-heading sideslips; and a deceleration and acceleration maneuver. A slow-flight maneuver was designed that involves pulling back on the stick to achieve a specified deceleration to capture the minimum speed. This maneuver was done for level and banked flight. A simulated engine-failure maneuver also was conducted that involves retarding an outboard engine to its minimum throttle setting, stabilizing flight, and then performing a heading capture.

The takeoffs were conducted with the canard extended and the nose at an 11-deg droop. The nominal approach and landing was a visual approach with the canard extended, gear extended, nose at a 17-deg

droop, and autothrottle engaged. Approach and landing characteristics also were evaluated with off-nominal conditions such as a lateral offset, the canard retracted, and the nose up. Evaluations using the throttle manually and the instrument landing system localizer also were made. Table 2 shows a brief description of these maneuvers and flight conditions. A detailed description from reference 1 is given in the appendix.

Table 2. Summary of maneuvers and conditions evaluated in the Tu-144LL handling qualities program.

| Maneuver | Condition | | Configuration |
	Altitude, km (m.s.l.)	Mach number	
Integrated test block	2	≈ 0.4	Takeoff
	2	≈ 0.4	Clean
	2	≈ 0.4	Nominal approach
	9	0.9	Clean
	17	2.0	Clean
Slow flight	2	≈ 0.4	Takeoff
	2	≈ 0.4	Nominal approach
	9	0.9	Clean
Simulated engine failure	2	≈ 0.4	Nominal approach
	9	0.9	Clean
	17	2.0	Clean
Terminal area	Pattern		Nominal
			Canard retracted
			Lateral offset
			Instrument landing system localizer
			Noseup
			Manual throttle

In addition, the pilots evaluated standard tasks such as leveling off and maintaining subsonic and supersonic cruise altitude, making level turns at supersonic cruise conditions at a speed of Mach 2.0, and climbing to and descending from supersonic cruise flight.

Comments Regarding Pilot-Generated Data

Because of the lack of simulator support, inexperience with flying the airplane, and the limited number of flights, the evaluation team decided not to collect Cooper-Harper ratings. Such ratings could

be misleading, as the ratings might reflect a "learning curve" in flying the airplane with no possibility for repeating maneuvers to eliminate the effect.

Adequate and desired performance criteria were not defined; thus, the primary data collected from these flights are pilot comments. During the postflight interviews, however, an assessment of flying quality "levels" was made (ref. 4).

SUMMARY OF PILOT COMMENTS

The pilot comments summarize the assessment of the up-and-away handling qualities of the airplane. The summary is compiled from pilot commentary (ref. 1), transcripts of postflight interviews, and personal discussions with both pilots.

Lateral-Directional Characteristics

Because lateral-directional characteristics may affect pilot assessment of longitudinal characteristics, the lateral-directional flying qualities are briefly discussed here. Both pilots commented on heavy wheel and pedal forces. Although wheel forces required to produce reasonable roll rates were a significant deficiency warranting modification, the pilots assessed the dynamics of the airplane as "level 1" (ref. 4) in the lateral-directional axis. The roll response of the airplane, although somewhat slow, was considered very predictable and well-damped.

Maneuvers such as bank-angle captures, steady level turns, and steady-heading sideslips were easy to perform, although the steady-heading sideslips required large pedal forces. Yaw damping was also considered satisfactory, and the pilots commented that heading captures were easy to perform. The same comments applied for all configurations and flight conditions tested.

Longitudinal Characteristics

Column forces in the pitch axis, although moderate to heavy, were not as significant a deficiency as in the lateral axis. The overall aircraft dynamics were assessed by the pilots as "level 2" (ref. 4). Table 3 summarizes the main points of the pilot evaluation.

Pitch-Attitude Dynamics

This assessment was influenced, in part, by sensitive pitch-attitude dynamics. Both pilots noticed tendencies to bobble during pitch-attitude captures. While performing the subsonic pitch-attitude capture task in flight 21, pilot A noticed a tendency for pitch attitude to overshoot and bobble. Pilot B also noticed overshooting and bobbling while performing the pitch-attitude capture task at a speed of Mach 2.0. Pilot B remarked that small column deflections produced large pitch-attitude transients without any acceleration cues. This lack of cues resulted in a tendency to overcontrol the airplane.

Although the pitch-attitude sensitivity described typically was not noticed in other tasks, it may have also affected the pilot workload during the climb to and descent from the Mach-2.0 cruise condition. Both pilots indicated that controlling the pitch axis was a high-workload task during these portions of the flight. Pilot B indicated this workload was caused in part by pitch-attitude sensitivity in the airplane.

Table 3. Summary of pilot evaluations.

Flight phase	Comments regarding pitch attitude	Comments regarding flightpath
Subsonic cruise	• Overshooting and bobbling. • Small column deflections produce large pitch-attitude transients with no motion cues. • Easy to compensate by reducing urgency.	• Leveling off and maintaining altitude easy.
Climb to and descent from supersonic cruise	• High workload. • Pitch-attitude sensitivity. • Small column deflections produce large pitch-attitude transients with no motion cues.	• Altitude rate control difficult because of combined effect of pitch-attitude sensitivity and flightpath angle lag. Leads to overcontrolling flightpath angle. • Difficult to find correct pitch-attitude.
Supersonic cruise	• Overshooting and bobbling. • Small column deflections produce large pitch-attitude transients with no motion cues. • Easy to compensate by reducing urgency.	• Leveling off and maintaining altitude easy.

Although the pilots felt the VRI was a useful display that made the task possible, maintaining the desired pitch profile was described as a full-time job. These comments probably are related to maintaining the final pitch-attitude response. Pilot A commented that the initial pitch-attitude response did not feel too quick or abrupt.

These comments appear to depend on the level of aggressiveness with which the various tasks were flown and the level of experience in flying the airplane. For flight 23, pilot A consciously monitored how aggressively pitch attitude was tracked during the pitch-attitude capture maneuver. By easing off and planning for the overshooting of pitch attitude, the pilot felt the pitch-attitude response was more predictable, making it relatively easy to achieve and hold the target pitch attitude. No oscillations in pitch attitude were noticed with this technique. Also, Pilot B learned to fly the pitch reference indicator much more efficiently as the flight progressed. Pilot B gradually learned to ramp down the pitch-axis gains to avoid overcontrolling the pitch axis.

Flightpath Dynamics

Comments concerning flightpath control were collected when leveling off at subsonic and supersonic cruise conditions, and during the climb to and descent from supersonic cruise conditions. Pilot B commented that vertical speed or flightpath control was difficult when following the VRI during the

climb because of two effects: the pitch-attitude sensitivity previously noted, and a perceived lag between pitch-attitude and flightpath responses. How much of this lag might be caused by instrumentation lag and how much by aircraft dynamics is unclear. Pilot B stated that the combination of the pitch-attitude sensitivity and the flightpath lag affected the ability to do the flightpath tracking task, causing tendencies to overcontrol pitch attitude and ultimately flightpath. Pilot A commented that finding the correct pitch attitude to maintain the climb profile was difficult and required constant corrections. This difficulty possibly was affected by the phugoid dynamics of the airplane as well.

Pilot B stated that capturing the cruise altitudes at speeds of Mach 0.9 and Mach 2.0 was easy to perform, but indicated some readjustments were required between power setting and pitch attitude to retrim after performing parameter identification maneuvers at the supersonic condition. In addition, Pilot B commented that maintaining altitude during the turn at a speed of Mach 2.0 was much easier than following the profile during the climb. All that was required in the turn was for the pilot to keep pitch attitude within 3° to 3.5° and otherwise make no other inputs. However, pilot A required more effort than Pilot B to maintain the supersonic cruise altitude because of difficulty in finding the right pitch attitude. Again, this difficulty may have been influenced by the phugoid dynamics of the airplane.

Additional Factors Influencing Pilot Comments

The comments here generally apply to all configurations and flight conditions tested; however, three caveats with regard to the pilot comments should be noted. The first caveat is that during the transition between subsonic and supersonic cruise, several fuel transfers were conducted to maintain a tight control on center-of-gravity location. These transfers produced trim changes that created a high-workload task for the pilot.

The second caveat is the resolution of the pitch-axis ladder. Although the pilots felt the ladder was a useful display, it has a much finer resolution than the attitude display indicators to which they were accustomed, thereby allowing for much more precise pitch-attitude tracking than normal. Having the less-precise scale to which they are accustomed would possibly induce the pilots to fly a less-demanding task, thereby changing their impressions of the airplane. The third caveat is that the lack of visual contact with the horizon at many conditions contributed to the difficulty in pitch-attitude tracking.

Controller Issues

Both pilots commented on adverse control harmony caused by heavy roll forces on the wheel and moderate pitch forces on the column. While applying the heavy turning forces necessary to get a desirable roll rate, the pilots tended to put inadvertent pitch inputs into the column that produced relatively large pitch transients. As a result, cross-coupling between the axes was evident.

The pilots commented that high throttle friction necessitated making throttle setting changes using two of the four levers at a time. Although throttle friction increased workload, the pilots could maintain airspeed during approach on the backside of the drag curve with a lot of attention. Some overcontrolling of airspeed was noticed by both pilots during acceleration and deceleration tasks and approaches. Also, using the throttle to correct for airspeed errors when using the VRI profile was difficult. Pilot B commented that one must either accept a slow convergence back to the profile or adjust pitch attitude. However, controlling airspeed while acquiring altitude at cruise conditions was adequate.

ANALYSIS

The Neal-Smith criterion (ref. 5); pitch bandwidth criterion (ref. 6); flightpath bandwidth criterion (ref. 7); and criteria on the short-period damping, time delay, control anticipation parameter (CAP), and phase delay ($\omega_{sp} * T_{\theta_2}$) from the flying qualities military standard (ref. 4) were applied to Tu-144LL data to determine whether their use would provide insights into the flying qualities of large supersonic vehicles. The Tu-144LL data used in the application of the criteria were generated from a fast Fourier transform of frequency-sweep time histories conducted in flight.

Where appropriate, handling qualities flight data from the YF-12, XB-70, and SR-71 aircraft were used to add insight into the Tu-144LL analysis. However, not all of the quantitative data necessary to apply some of the criteria were available for the YF-12 and XB-70 aircraft. For the YF-12 aircraft, enough information existed in reference 3 to extract the test condition of the pilot evaluations. Because of the similarity of the YF-12 and the SR-71 aircraft in the longitudinal axis, a flight-validated SR-71 simulation was used to approximate the unavailable YF-12 data. Reference 8 provides further information on handling qualities data from these aircraft, including references to evaluations of the aircraft conducted approximately 30 years ago by NASA Dryden. Reference 9 contains additional information regarding more recent flight tests on SR-71 handling qualities.

All the handling qualities data used in this analysis were generated from evaluations of large, heavy, Class III aircraft (ref. 4) that had low to medium maneuverability. Comparisons of these data primarily were made to "category C" criteria (ref. 4). Experience has shown that category C correlates best with pilot comments and ratings for much of the supersonic flight profile typical of these aircraft. Although defined as criteria for takeoff, approach, and landing, category C is applicable to evaluations of these aircraft because tasks requiring gradual maneuvering with accurate flightpath control were flown.

Neal-Smith Criterion

The Neal-Smith criterion involves closing the loop around the pitch attitude–to–stick deflection transfer function. A lead/lag compensator and pure time delay are inserted into the loop to represent a simple pilot model. The compensator is adjusted to meet specific closed-loop characteristics. The characteristics of the closed-loop frequency response are defined as –90° of phase at the bandwidth frequency and no less than –3 dB of droop (fig. 8). The bandwidth frequency represents the urgency of the piloting task being conducted and is generally chosen based on flight phase. The criterion is established based on the lead required of the compensator to meet the characteristics and the maximum amplitude, or resonant peak, of the frequency response of the closed-loop (that is, the compensator and airplane) system.

For these data, a time delay of 0.25 sec (as recommended in reference 4) was chosen. Bandwidths of 1.0, 1.5, 2.0, and 2.5 rad/sec were analyzed, representing increases in the urgency of the task.

Figure 9 shows the results of applying this criterion to TU-144LL up-and-away data. Several interesting characteristics are observed. For subsonic cruise flight, the data indicate that the airplane exhibits level-1 characteristics as the bandwidth increases from 1.0 to 2.0 rad/sec, despite the increase in pilot lead required. As the bandwidth increases from 2.0 to 2.5 rad/sec, the data indicate an increase in lead and resonant peak, placing the predicted handling qualities in the level-2 region. These results are consistent with pilot comments regarding the pitch-attitude capture task, which indicate a tendency to bobble as a function of how urgently the maneuver is flown.
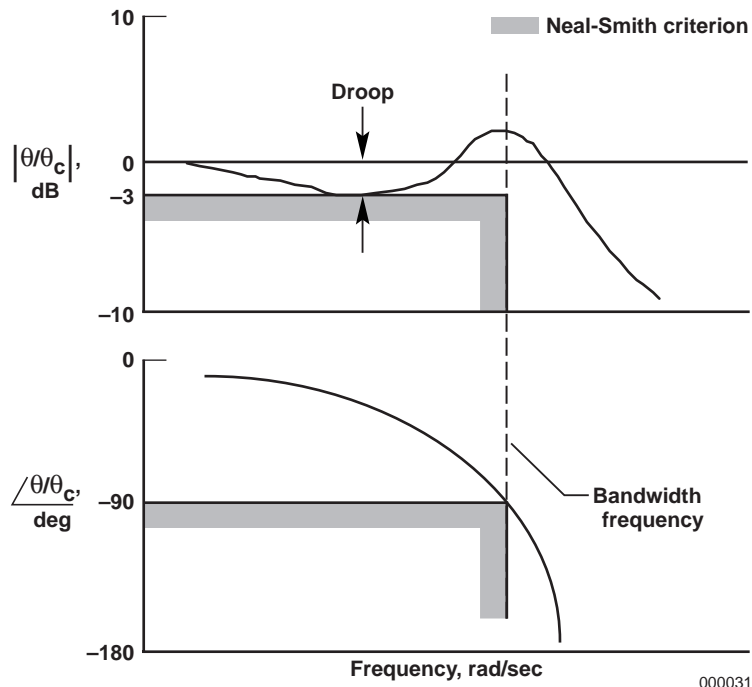
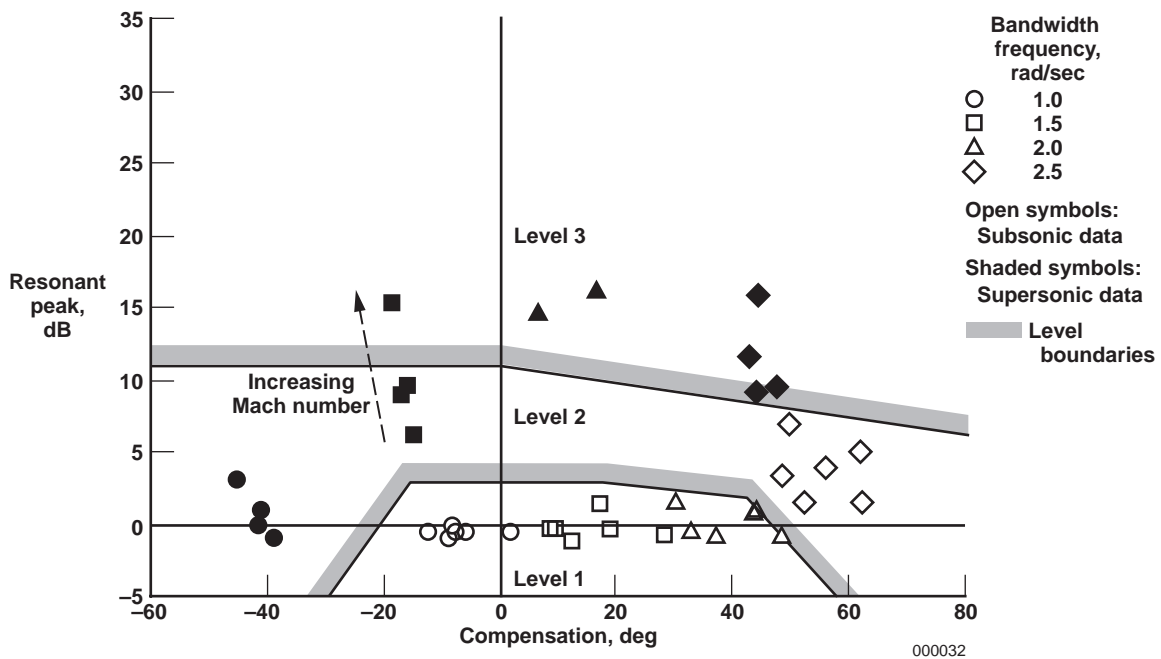Figure 8. Illustration of Neal-Smith criterion application.

Figure 9. Results of Neal-Smith analysis.

Figure 10 shows two time histories of pitch-attitude captures from flights 21 and 23, flown by the same pilot at a speed of Mach 0.9, illustrating the tendency to bobble in the pitch axis. During flight 21, the pilot pushed on the column to capture a pitch-attitude change of approximately –2°. At 6–7 sec, while attempting to capture the target value, the pilot sensed that the pitch attitude was overshooting, which prompted the pilot to pull back on the stick, overcorrecting. An attempt to compensate for overcorrecting led to overshooting in the other direction. This type of oscillation in pitch attitude was observed for three or four cycles. Pilot comments after the flight confirmed that the pitch axis was sensitive and tended to bobble, correlating to the Neal-Smith analysis at 2.5 rad/sec bandwidth, which is where the resonant peaks are at or above the requirement for level 1 and excessive lead compensation is required.
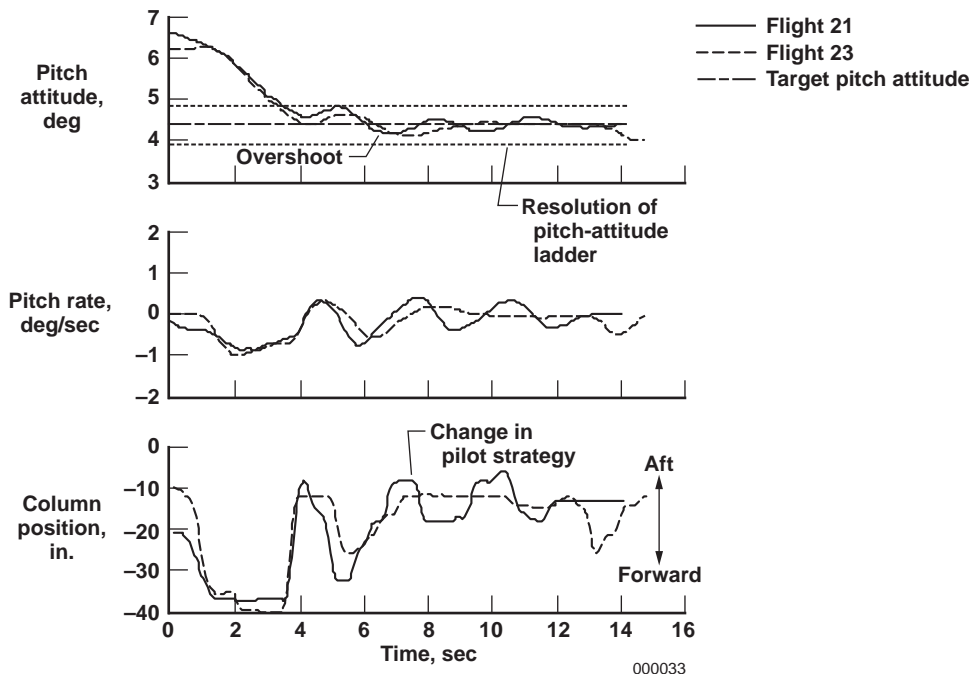
Figure 10. Comparison of pitch-attitude task time histories from flight 21 and flight 23.

For flight 23, the pilot reduced the urgency of the maneuver. Instead of attempting to pull back on the column when pitch-attitude overshooting was sensed (at approximately 7 sec), the pilot kept the pitch input constant in an attempt to achieve the target value by predicting the amount the pitch attitude drops back. As figure 10 shows, this technique reduced the tendency for the pitch attitude to oscillate. Pilot comments from this flight indicate that the pitch dynamics were well-damped, making the target pitch attitude relatively easy to achieve and maintain. These comments correlated well with the Neal-Smith data for bandwidths less than 2.0 rad/sec, which is where resonant peak and lead compensation requirements were reduced.

As figure 9 shows, the supersonic cruise data, ranging from Mach 1.25 to 2.00, indicate that more lag compensation is required for a given bandwidth than was required for the subsonic data. For low bandwidths of 1.0 to 1.5 rad/sec, the Neal-Smith data indicates a level-2 airplane. For bandwidths of 1.0 rad/sec, the resonant peak is low enough not to be a significant detriment. But the lag compensation required to meet the Neal-Smith criterion is large enough to elicit pilot comments on the abruptness of the pitch-attitude response. For bandwidths of 1.5 rad/sec, the resonant peak is high enough to elicit comments on pitch sensitivity.

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As the bandwidth increases from 1.5 to 2.0 rad/sec, increases in the resonant peak push the data into the region of "level 3" (ref. 4). Note that only two data points are plotted for the 2.0 rad/sec bandwidth. Application of the Neal-Smith algorithm produced questionable results for two of the supersonic data points. These data points are not shown. Interestingly, as the bandwidth increases from 2.0 to 2.5, the pilot lead increases but the resonant peak reduces. However, the tradeoff between lead compensation and resonant peak places the data near the boundary of levels 2 and 3.

Pilot comments on sensitive pitch-attitude dynamics during the climb to and the descent from supersonic cruise flight and pitch-attitude bobbling during pitch-attitude captures are indicative of a high resonant peak on the Neal-Smith plane. Pilot A also noted during pitch-attitude captures that the initial pitch response was not too quick or abrupt, which would indicate that pilot lag is not a problem. Thus, the results of the Neal-Smith analysis for bandwidths in the region of 1.5 rad/sec appear consistent with pilot comments. Because the climb to and descent from supersonic cruise flight could be considered a category C task, the correlation with a bandwidth of 1.5 rad/sec is supported by reference 4, which states that the appropriate bandwidth for category C tasks other than landing is 1.5 rad/sec. Both pilots learned that reducing their pitch-axis urgency created a stable, acceptable, closed-loop pitch response. Because reducing urgency is comparable to reduced bandwidth, these pilot comments become less consistent with the Neal-Smith analysis, which predicts an unacceptably abrupt initial pitch response caused by the lag compensation.

One interesting aspect of the analysis (fig. 9) is the large lag compensation observed for supersonic data at low bandwidths. This phenomenon can be explained by the decrease in $1/T_{\theta_2}$, which is primarily caused by increasing Mach number (fig. 11). As $1/T_{\theta_2}$ decreases, pitch-rate overshooting increases, requiring the pilot to make less abrupt inputs. Figure 12 shows a comparison of the pitch attitude–to–column deflection frequency response at speeds of Mach 0.9 and Mach 2.0. The comparison shows that the effect of decreased $1/T_{\theta_2}$ in the data for Mach 2.0 is the large, shelf-like characteristic in the magnitude data for frequencies lower than 1.5 rad/sec.
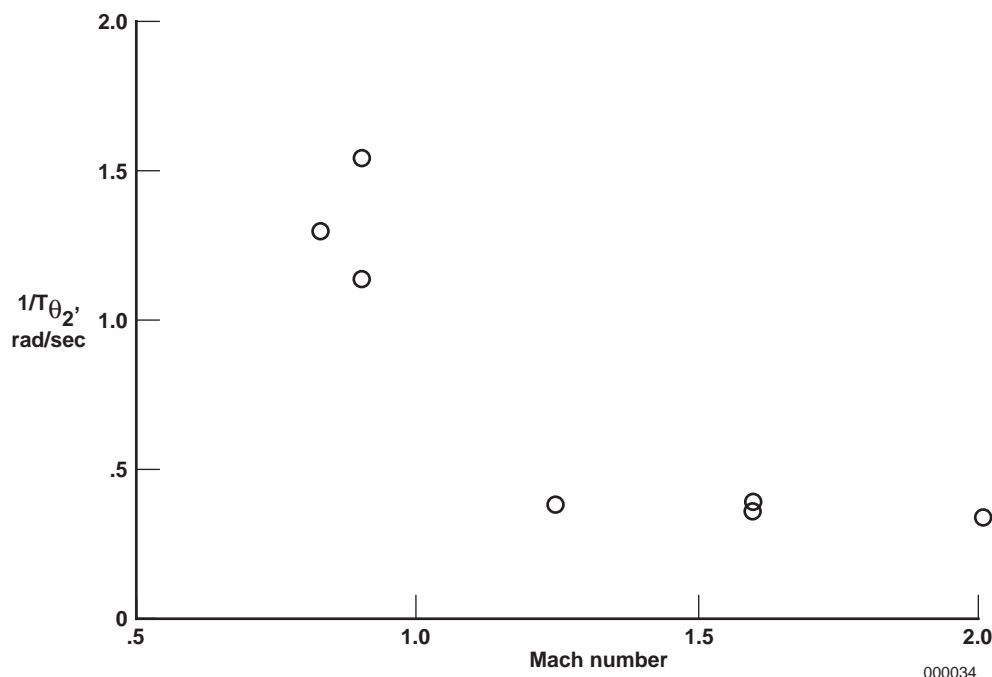

Figure 11. The value of $1/T_{\theta_2}$ as a function of Mach number.
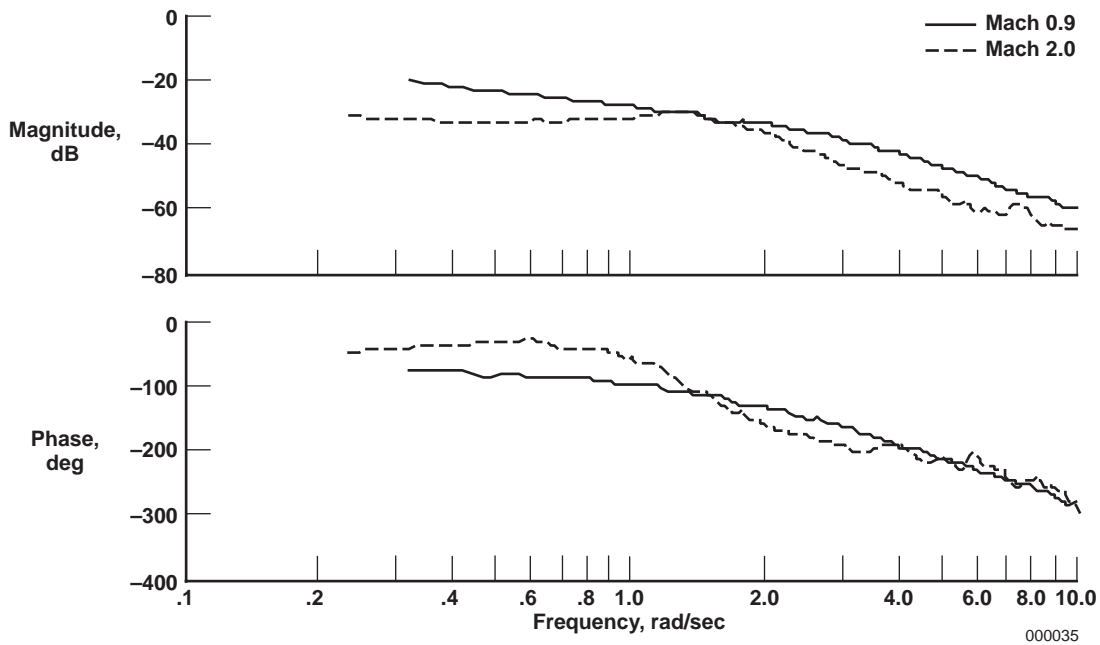
Figure 12. Comparison of pitch attitude–to–column deflection bode plot for subsonic cruise and supersonic cruise conditions.

The effect of this shelf on the Neal-Smith analysis is observed in the plot of the data for Mach 2.0 in the Nichols plane (fig. 13). This figure shows two sets of data, one without compensation and the other with lag compensation added. Both sets of data include compensator time delay and adjustments to the compensator gain. The shelf characteristic shows up in the uncompensated data as relatively flat magnitude deviations (between –2 and 0 dB) in the phase angle region of approximately –60° to –150°. Because of the flattened region, the bandwidth frequency has been pushed to relatively high values of phase angle (approximately –150°).

An "elbow" in the uncompensated data is also observed at approximately –60° of phase, similar in characteristic to vehicles with large amounts of inherent lead. Too much lead, however, exists in the system. That is, in order for the Neal-Smith algorithm to meet its criterion, this "elbow" in the data must be compensated such that it becomes tangent to the –3 dB closed-loop magnitude curve, which requires some significant lag compensation. Application of lag moves the "elbow" in the data closer to meeting its criterion, as observed by the compensated data (fig. 13). But lag compensation also pushes the bandwidth frequency to even higher phase values, thus increasing the resonant peak. In essence, the shelf-like characteristic indicates that the Mach-2.0 configuration has inherently more lead than does the Mach-0.9 configuration. Hence, control of pitch attitude requires more lag compensation and produces higher resonant peak as Mach number increases. In figure 9, this observation is highlighted for the 1.5-rad/sec bandwidth data, which shows that both pilot lag and resonant peak increase as Mach number increases.

This phenomenon has also been observed with SR-71 data (ref. 8). Figure 14 shows large amounts of pilot lag required for the Neal-Smith analysis of SR-71 Mach-3.0 data. However, pilot comments of SR-71 evaluations indicate pilot lead is required and that the airplane is level 1. This lack of correlation between the SR-71 pilot comments and the Neal-Smith analysis was traced to the use of an inertially derived vertical speed indication as the primary pilot cue, not pitch attitude as used by the Neal-Smith
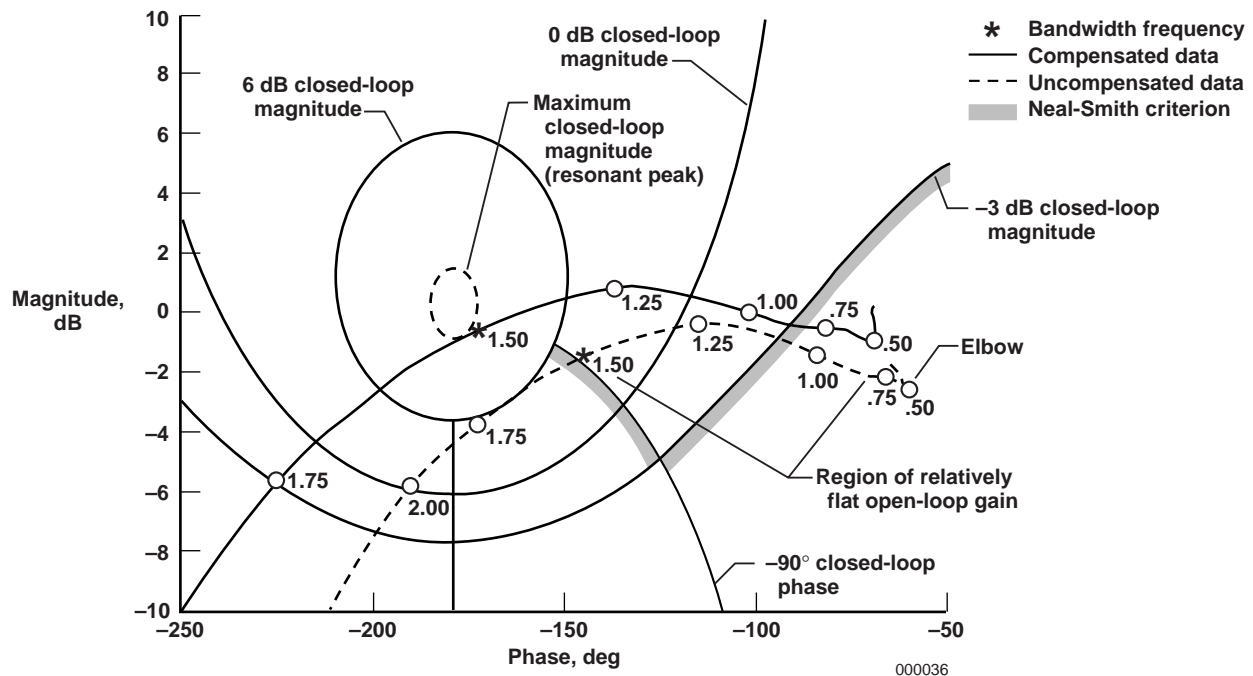
17

Figure 13. Comparison of pitch attitude–to–column deflection frequency responses at supersonic cruise for uncompensated and lag-compensated data.
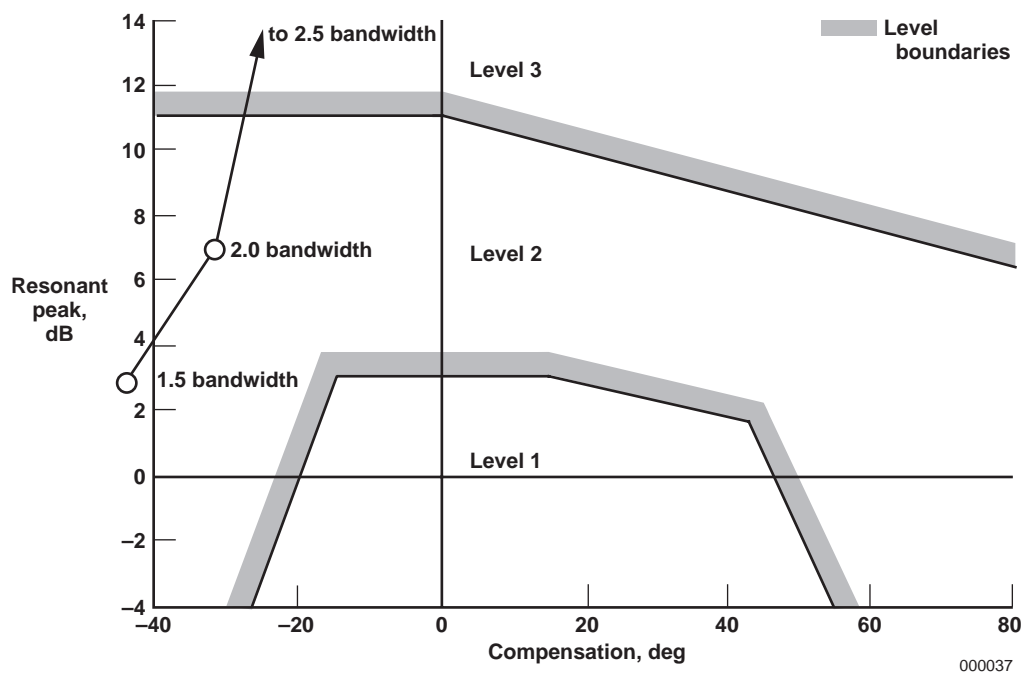

Figure 14. Neal-Smith analysis of pitch attitude–to–stick deflection frequency response of the SR-71 aircraft at Mach 3.0.

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criterion. Vertical speed lags pitch attitude by the time constant T_{θ_2}, as shown in the following equations.

$$\gamma/\theta \ = \ 1/(T_{\theta_2} * s \ + 1) \tag{1}$$

$$V * \sin\gamma \ = \ \dot{h} \tag{2}$$

Assuming relatively constant airspeed, the integral of normal acceleration is shown in the following equation to approximately equal vertical speed:

$$g * \int Nz \ dt \ = \ \int V * \dot{\gamma} \ dt \approx V\gamma \approx \dot{h} \tag{3}$$

Performing the Neal-Smith analysis using a frequency response of the integral of normal acceleration, or vertical speed, at the pilot station instead of pitch attitude resulted in good agreement with the pilot comment data for bandwidths to a maximum of 1.5 rad/sec (fig. 15; ref. 8). Curiously, the pilot comments for both the SR-71 and the Tu-144LL aircraft in typical supersonic flight tasks appear to correlate with the Neal-Smith analysis for bandwidths near 1.5 rad/sec, which according to reference 4 is representative of the category C flight phase.
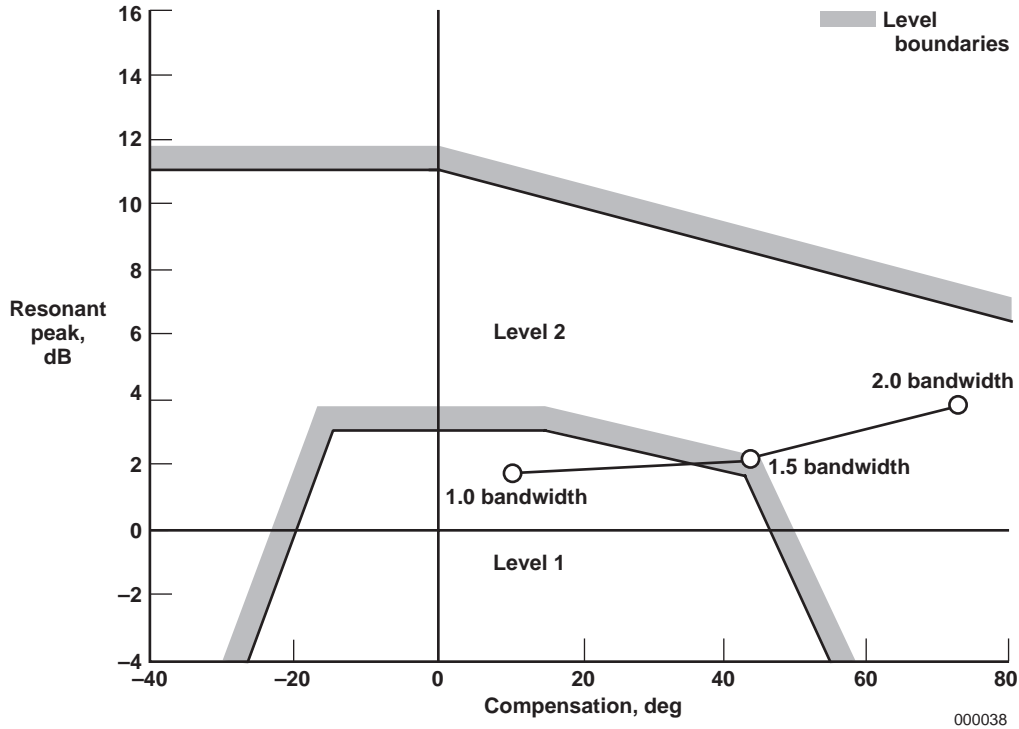
Figure 15. Neal-Smith analysis of vertical speed at the pilot station–to–stick deflection frequency response of the SR-71 aircraft at Mach 3.0.

From these SR-71 results, one might ask whether providing an inertially derived vertical speed would improve Tu-144LL flying qualities characteristics. The answer is predicted through a Neal-Smith analysis using the integral of normal acceleration–to–column deflection frequency response (fig. 16). The results, overplotted with the SR-71 data from figure 15, show that for low bandwidth, the flying qualities are level 1. In this region of bandwidths, the flying qualities would be improved. However, more pilot lead generally is required for the Tu-144LL than the SR-71 aircraft; and for a bandwidth of 1.5 rad/sec, the Tu-144LL airplane requires enough pilot lead to be level 2.
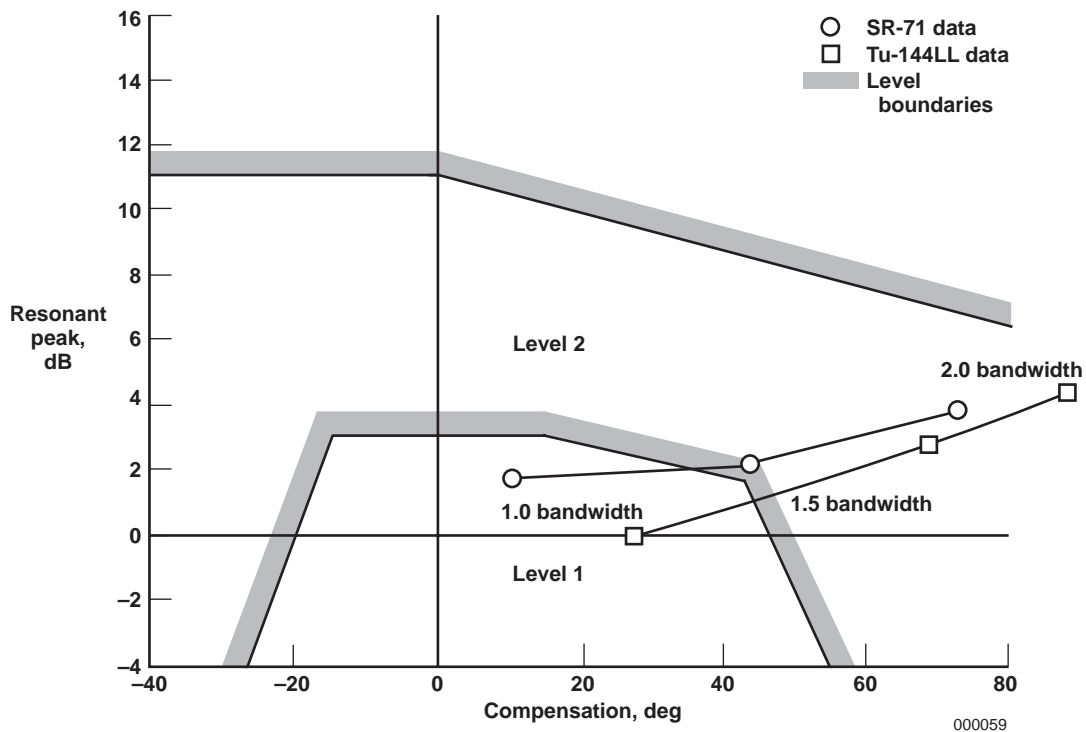
Figure 16. Neal-Smith analysis using vertical speed at the pilot station frequency response of the SR-71 aircraft at Mach 3.0 and the Tu-144LL airplane at Mach 2.0.

Damping, Time Delay, Control Anticipation Parameter, and Phase Delay Criteria

A low-order equivalent system approach was applied to flight-generated frequency response data to determine short-period damping, time delay, CAP, and $\omega_{sp}*T_{\theta_2}$. These data were then applied to the military standard criteria (ref. 4).

Figure 17 shows the short-period damping and time delay as a function of Mach number with the military standard handling qualities requirements for category C flight overplotted. As Mach number increases, the short-period damping decreases. At Mach 1.2, the damping estimates are near the boundary of level 1 and level 2 and stay relatively constant to Mach 2.0. Although the damping dips slightly below the boundary, it is close enough to consider the short-period damping to be level 1 throughout the envelope. This assumption for the supersonic data is corroborated when considering a comparison of short-period damping estimates of the YF-12, XB-70, and SR-71 aircraft given in reference 8, in which damping ratios greater than 0.15 were considered level 1. These data (fig. 18) show the military standard requirement may be too restrictive for the type of tasks being performed. Several level-1 pilot ratings exist for damping estimates less than 0.35, falling outside the shaded region of correlation.
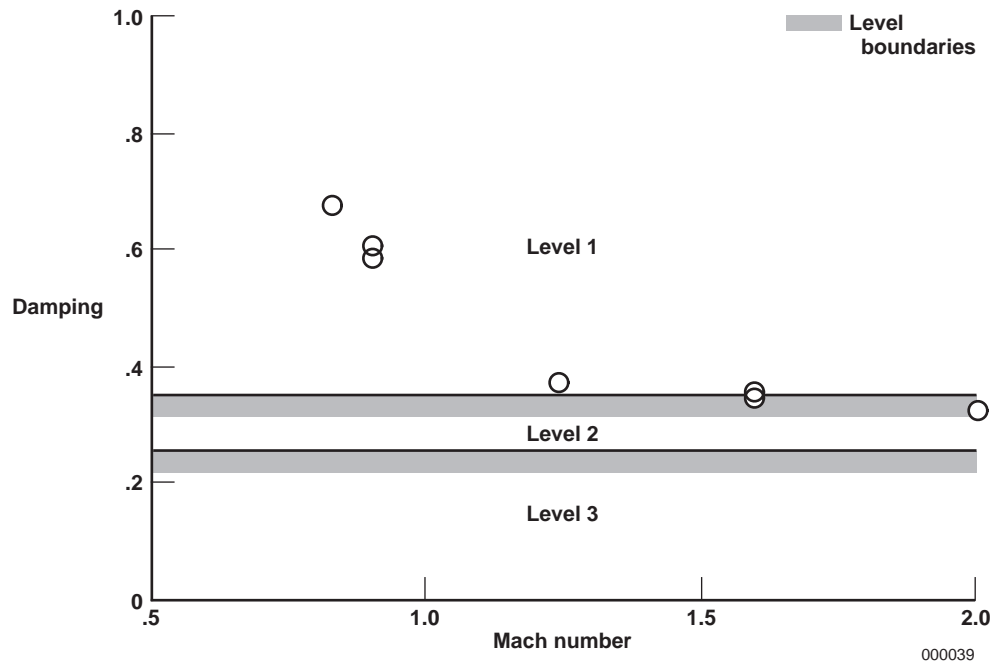
(a) Parameter estimation results of short-period damping.
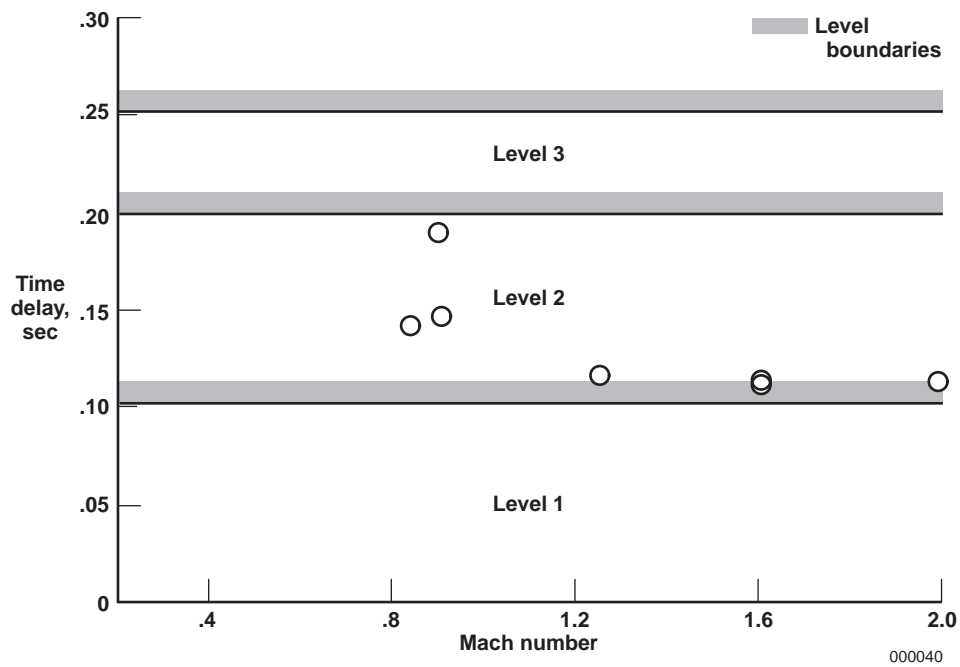
(b) Parameter estimation of time delay.

Figure 17. Parameter estimation results of short-period damping and time delay as a function of Mach number.
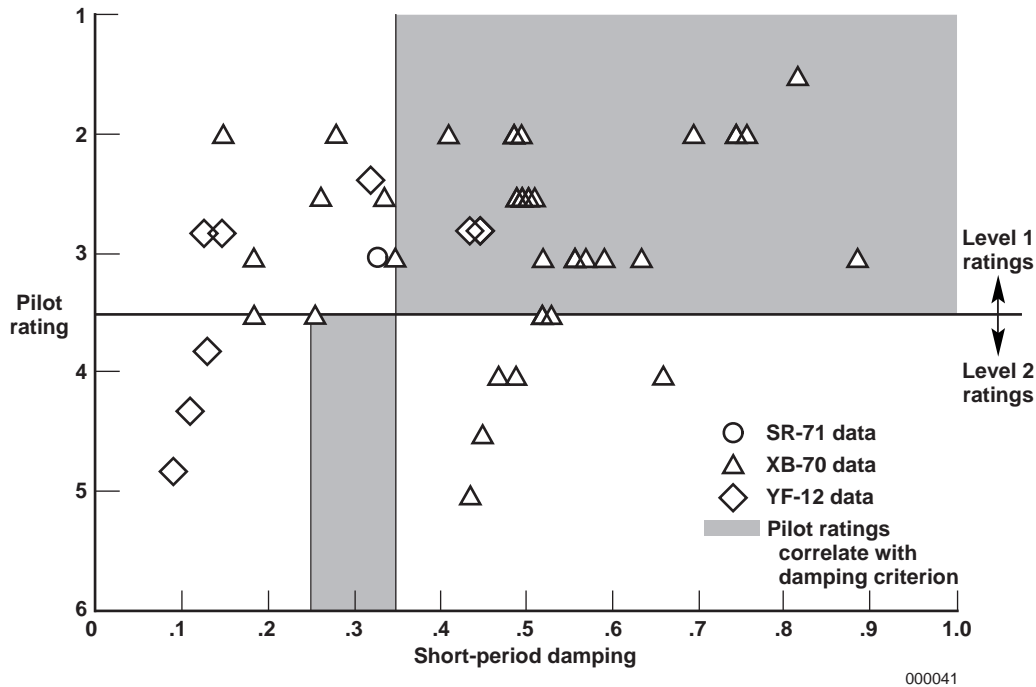
21

Figure 18. Short-period damping estimates of YF-12, XB-70, and SR-71 aircraft compared with military standard "category C" requirements.

At Mach 0.9, the time delay estimates (fig. 17) indicate that the delay is 150 msecs. As the Mach number increases to 2.0, the time delay estimates converge to approximately 110 msecs. Although these data fall within the level 2 region, the military standard suggests that the requirement is too stringent. In reality, the real limit for level 1 may be as great as 250 msecs for Class III airplanes. This suggested limit, coupled with the comments that no significant delays were perceived in the Tu-144LL airplane, indicate that these estimates tentatively may be considered level 1.

Criteria on the CAP (ref. 10) and $\omega_{sp} * T_{\theta_2}$ in reference 4 establish requirements for the relationship between pitch-attitude and flightpath responses. An excessively low CAP implies that pitch acceleration cues are too small compared to the increase in load factor when changing flightpath. A low CAP therefore prompts an increase in pilot input until an initial pitching acceleration appropriate to the desired final normal acceleration is attained. This increased pitch acceleration leads to overshooting flightpath. Pilots typically complain that the initial response seems sluggish, compelling them to overcontrol the airplane. Conversely, if the CAP is too large, then the pitching acceleration is large compared to the normal load factor response and the pilot complains about an abrupt initial response. For too large or too small CAPs, oscillations in tracking flightpath can result.

Physically, $\omega_{sp} * T_{\theta_2}$ represents the lag between pitch-attitude response and flightpath response at the short-period frequency. If $\omega_{sp} * T_{\theta_2}$ is too small, the attitude and flightpath responses are nearly simultaneous and result in an abrupt heaving response and overshooting flightpath, similar in effect to a low CAP. Likewise, if $\omega_{sp} * T_{\theta_2}$ is too large, then too much lag exists between attitude and flightpath response and results in overshooting pitch rate by a large margin, similar to the case of a high CAP. Therefore, the same trends in the CAP and $\omega_{sp} * T_{\theta_2}$ data should predict similar pilot opinions.

Figure 19 shows an inverse relationship between the CAP and $\omega_{sp}*T_{\theta_2}$ as Mach number increases. The reason for the inverse relationship becomes clear by investigating the trends of the numerator and denominator of the CAP approximation:

$$CAP \approx \omega_{sp}^2/[(V*1/T_{\theta_2})/g] \qquad (4)$$
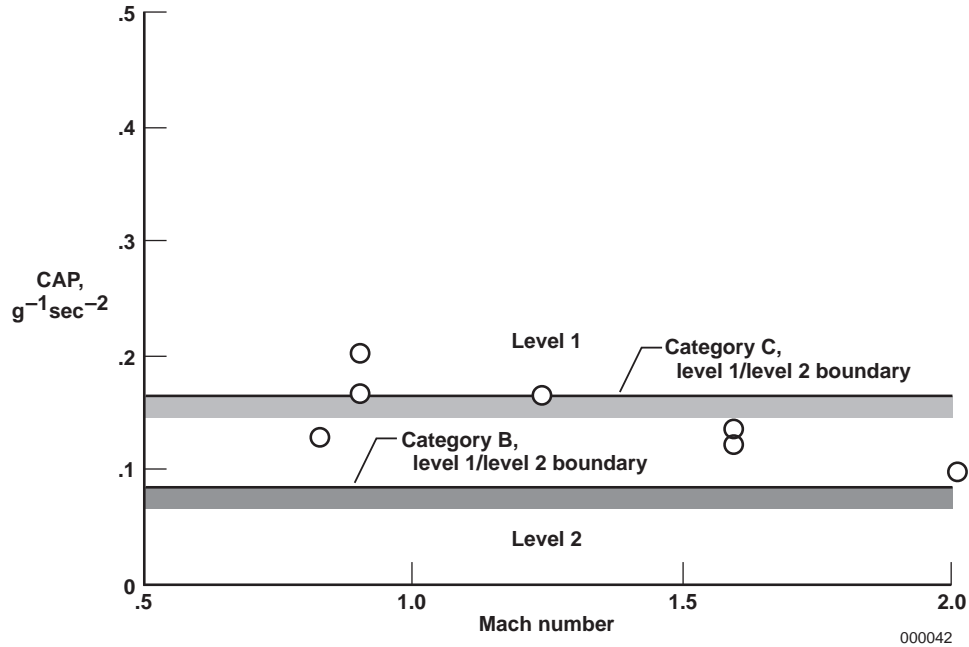
a) CAP.
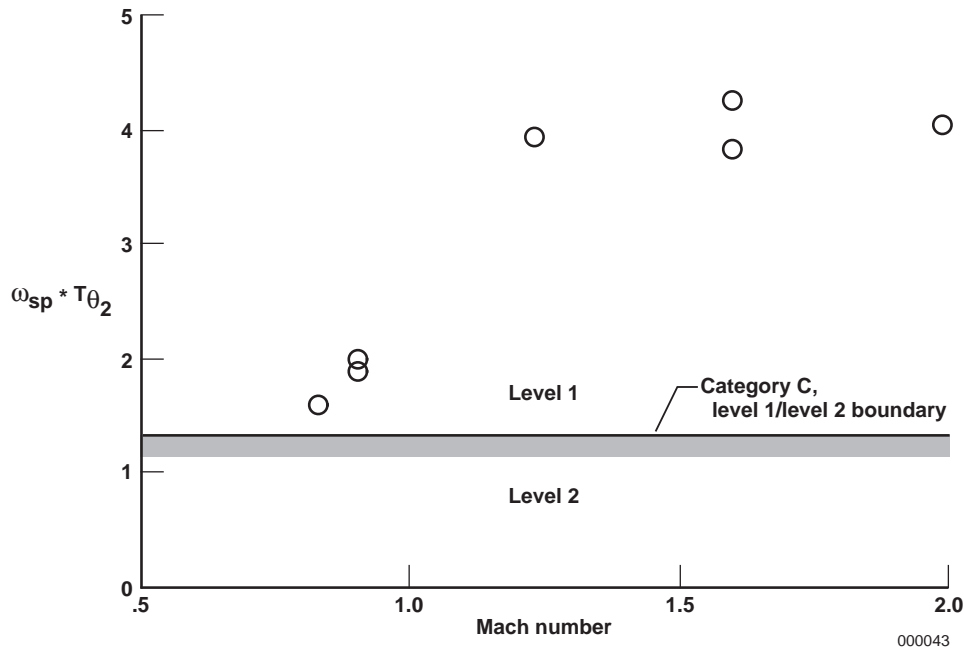
b) $\omega_{sp}*T_{\theta_2}$.

Figure 19. Comparison of $\omega_{sp}*T_{\theta_2}$ and CAP as a function of Mach number with military standard requirements overplotted.

Figure 20 shows the term in the denominator, $(V*1/T_{\theta_2})/g$, sharply decreases through the transonic region and then slightly increases with increasing Mach number. For Mach numbers greater than 1, the slight decrease in $1/T_{\theta_2}$ (fig. 11) is more than offset by the increase in airspeed. The net effect of the denominator is to increase the CAP through the transonic region and then decrease the CAP as Mach number increases. For the numerator, however, the decrease of ω_{sp} through the transonic region (fig. 21) appears to mitigate the transonic increase of the CAP denominator. For Mach numbers greater than 1, ω_{sp} remains relatively flat. Thus, the combined effect of the numerator and denominator is for the CAP to decrease with increasing Mach number. In the case of $\omega_{sp}*T_{\theta_2}$, the increase in T_{θ_2} more than offsets the decrease in ω_{sp}. Thus, $\omega_{sp}*T_{\theta_2}$ increases with increasing Mach number.
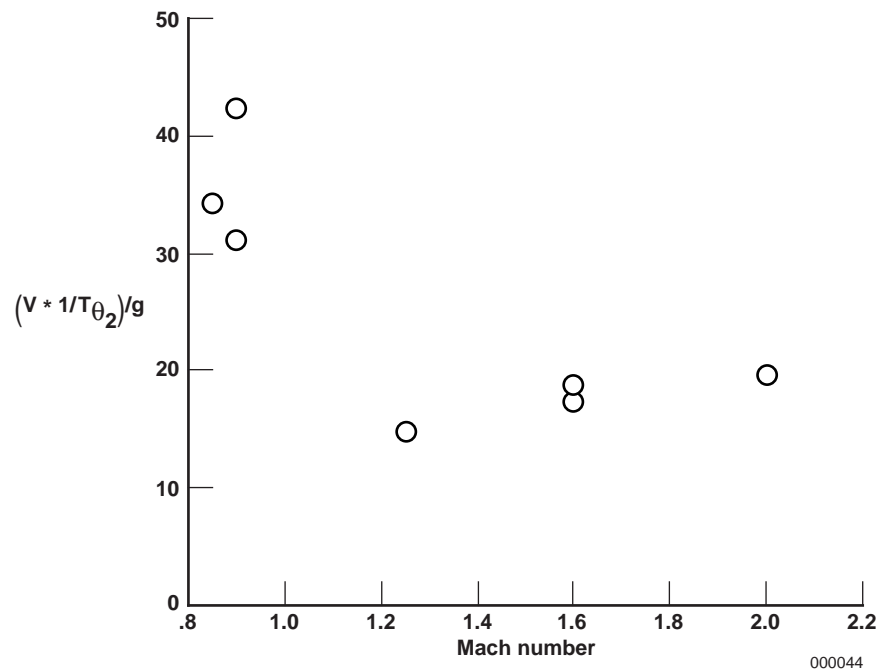

Figure 20. Trend of the CAP denominator as a function of Mach number.

Overplotted on figure 19 are the requirements for level 1 for category B and category C (ref. 4). For the CAP, the subsonic data is observed to be near the boundary of level 1 and level 2 for category C. As Mach number increases to 2.0, the CAP reduces below the category C boundary and near to but not below the category B boundary. For the $\omega_{sp}*T_{\theta_2}$ parameter, the data for Mach 0.9 are observed to be just above the boundary of level 1 and level 2 for category C flight and increase further into the level-1 region as Mach number increases to 2.0. Although the increase of $\omega_{sp}*T_{\theta_2}$ predicts improved flying qualities for increasing Mach number, the CAP predicts degradation. Because short-period damping and time delay were considered level 1, pilot comment and rating data for supersonic flight should be reflected in one of these two parameters and could help determine which, if either, of these two parameters is a better handling qualities predictor.

In the Tu-144LL airplane, pilot B commented during the pitch-attitude capture task that lack of motion cues resulted in overcontrolling tendencies. This comment appears consistent with low values of the CAP, which predict that small pitch acceleration cues are not being sensed (resulting in overcompensation). However, the pilots commented that flightpath control during the turn at Mach 2.0
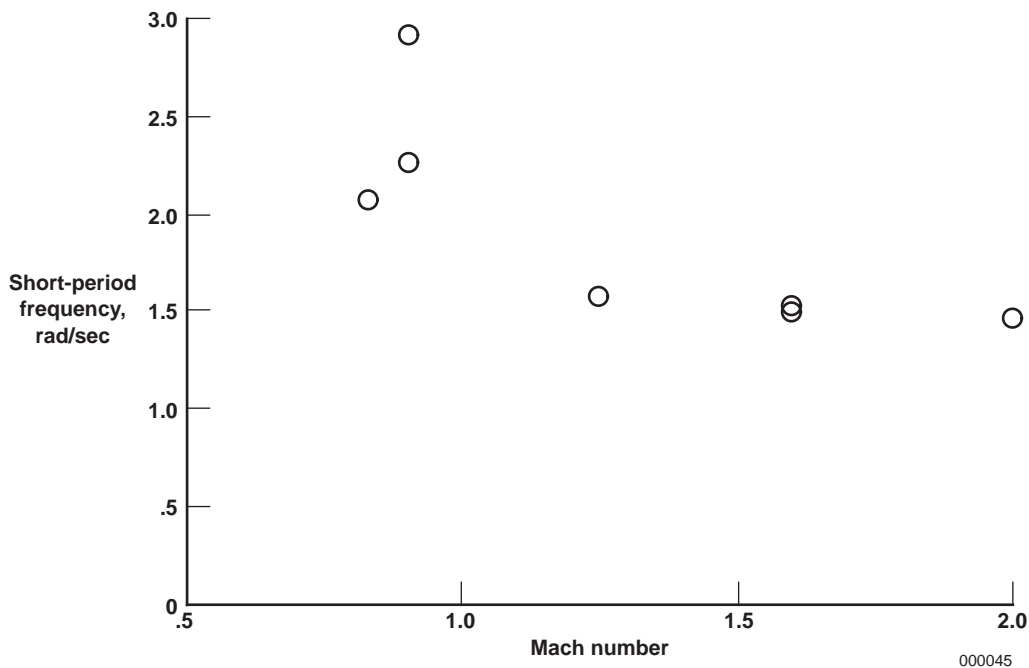
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Figure 21. Short-period frequency estimates as a function of Mach number.

was easy. The CAP data, however, which fall below the category C requirement, indicate the pilot should overcontrol flightpath for a precision task. This discrepancy can be explained by comparing YF-12, XB-70, and SR-71 values of the CAP to pilot evaluations of maneuvers where precision altitude control was required (ref. 8). Figure 22 shows the comparison with the military standard category C requirements overplotted. Data that correlate with pilot ratings fall within the shaded region. For the XB-70 and SR-71 data, the pilots were asked to control altitude to within 100 ft (30.49 m). The results show that the CAP parameter correlates well with category C requirements for maneuvers with altitude control at this level of precision.

Figure 23 shows a comparison of altitude perturbation, pitch-attitude perturbation, and longitudinal pilot input during a turn at supersonic cruise flight for flight 22 of the Tu-144LL and for the SR-71 aircraft. The comparison shows the Tu-144LL pitch-attitude and altitude traces exhibiting a significant phugoid oscillation compared with the SR-71 traces. Throughout most of the turn in the Tu-144LL airplane, pitch attitude oscillates approximately $\pm1°$ and altitude oscillates ±500 ft (152.44 m). In the SR-71 aircraft, the pilot did not allow oscillations in pitch attitude or altitude, constantly making corrections so that altitude stayed within the required 100 ft (30.49 m). These data indicate that the SR-71 pilot was more tightly controlling flightpath than the Tu-144LL pilot. Subsequent discussion with the pilot of flight 22 confirmed that no attempt to tightly track altitude was made during this portion of the flight. Thus, the turns at Mach 2.0 may be interpreted as a category B task, in which less precise flightpath control is required. Better correlation of pilot comments of the turn exist when comparing the CAP data (fig. 19) with the category B requirement, which allows lower values.
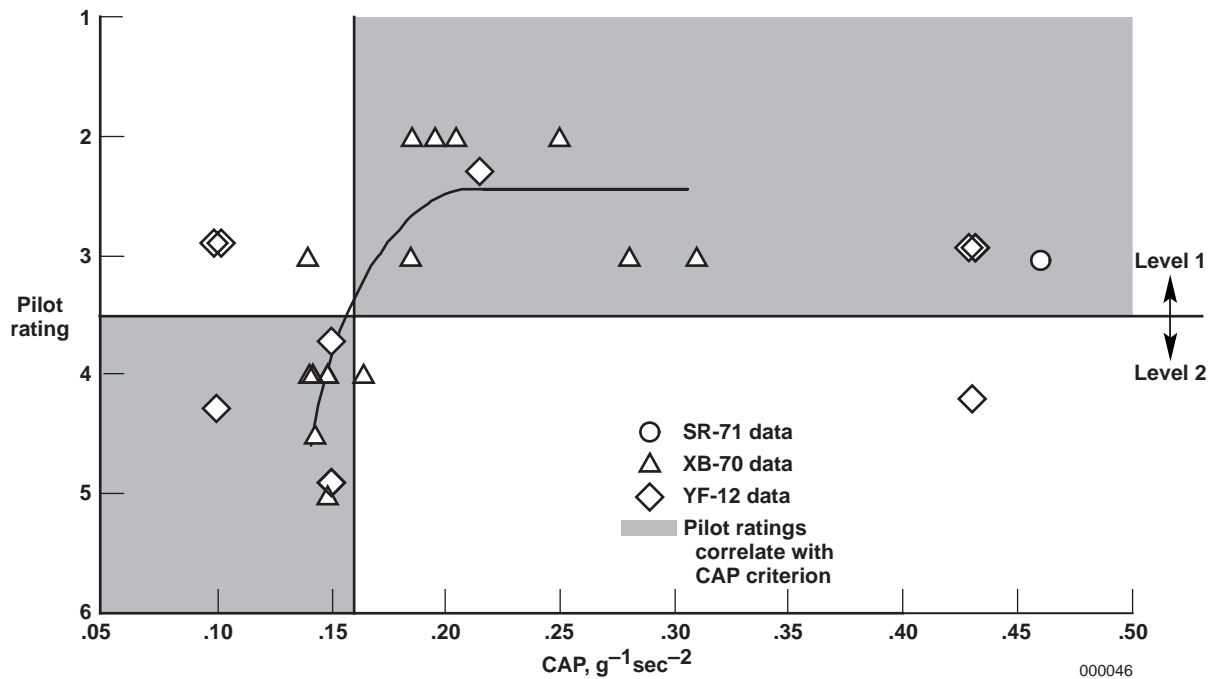
25

Figure 22. Comparison of the CAP of YF-12, XB-70, and SR-71 aircraft to military standard "category C" requirements.
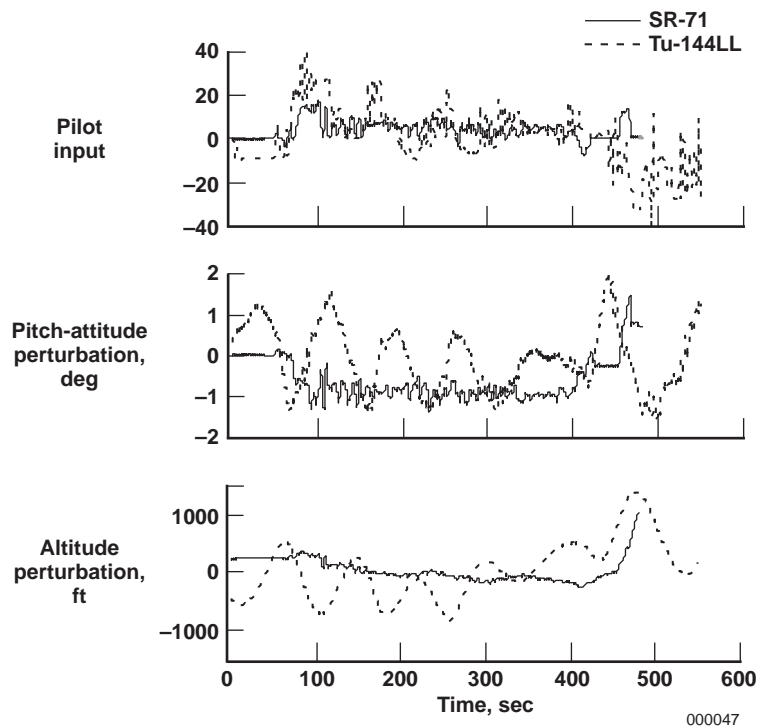

Figure 23. Comparison of time histories of the SR-71 and Tu-144 aircraft during turn at supersonic cruise.

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Maintaining the VRI profile during the climb to Mach-2.0 cruise flight may be a task requiring precise flightpath control. The pilot comments indicate that overcontrol in flightpath resulted from the combined effect of pitch-attitude sensitivity and a perceived lag between pitch attitude and flightpath. The pilot may have been noticing the increased lag between pitch attitude and flightpath predicted in figure 19 by the increased $\omega_{sp}*T_{\theta_2}$. However, the criterion predicts that the increased lag will have no detrimental effect on handling qualities, whereas pilot B's comments indicate some problems in vertical speed control exist. The comments correlate better with the CAP data, which does predict overcontrolling flightpath when compared to the category C requirement.

From the discussion above, the CAP appears to correlate better with the supersonic data than $\omega_{sp}*T_{\theta_2}$ does. The same observation was made for XB-70 data in reference 2 regarding an altitude tracking task considered a category C task. Figure 24 shows the same CAP and $\omega_{sp}*T_{\theta_2}$ data from reference 2 replotted. As shown in the TU-144LL data, the CAP decreases as Mach number increases. Pilot ratings correlated well with the military standard category C limits of 0.16 for the CAP, but in the region of constant $\omega_{sp}*T_{\theta_2}$, approximately equal to 7.5, the pilot ratings vary from 2 to 5.
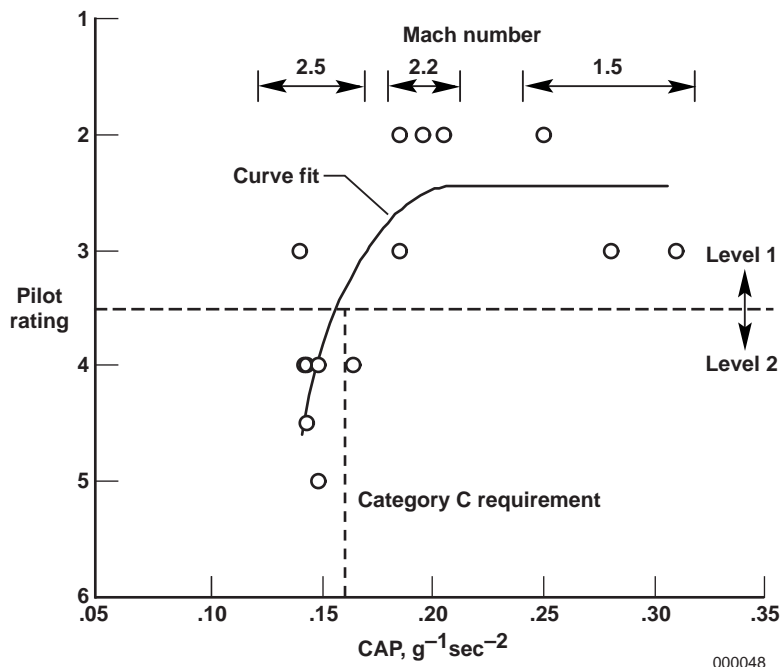
a) CAP criterion.

Figure 24. Comparison of XB-70 estimates of $\omega_{sp}*T_{\theta_2}$ and the CAP to pilot evaluation of an altitude tracking task.
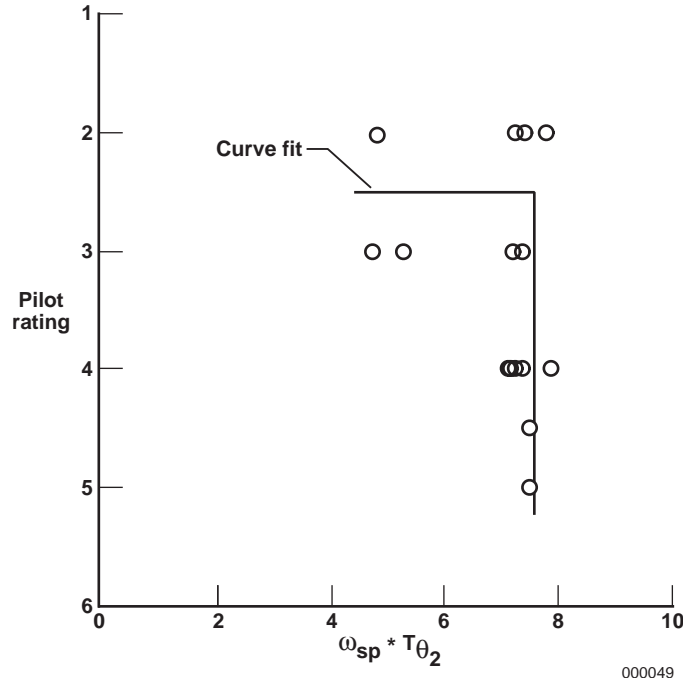
b) $\omega_{sp} * T_{\theta_2}$ criterion.

Figure 24. Concluded.

Bandwidth Criterion

The bandwidth criterion defined in reference 4 was used to analyze Tu-144LL pitch attitude–to–stick deflection frequency response data. The gain-limited bandwidth, defined as the frequency at the magnitude that is 6 dB greater than the magnitude at the phase crossover frequency; and phase-limited bandwidth, defined as the frequency where 45-deg phase margin exists, were calculated from the pitch attitude–from–stick deflection frequency response (ref. 6). The lesser of the two frequencies was considered the bandwidth frequency. The criterion places limits on the bandwidth frequency as a function of the phase delay, which is estimated from the phase at twice the phase crossover frequency:

$$\tau_p = \frac{\phi_{2\omega_{180°}} + 180°}{57.3(2\omega_{180°})} \tag{5}$$

Figure 25 shows application of the bandwidth criterion to Tu-144LL data for the category C flight phase. The bandwidth frequency can be considered to be the amount of bandwidth a pilot can apply to a vehicle before sensing the closed, pilot-in-the-loop system becoming too lightly damped or oscillatory. The criterion establishes requirements on how much bandwidth is desirable for a particular flight phase. The data (fig. 25) show that not enough bandwidth exists in the system to be considered level 1 because the minimum bandwidth desired for level 1 is 2.5 rad/sec. If the pilot were to try to achieve the desired bandwidth, the closed-loop system would result in an oscillatory response, which is apparently what occurred during the pitch-attitude tracking task. Initially, the pilots performed the task aggressively (with a more desirable bandwidth), which resulted in an oscillatory pitch response. By reducing the gain, the
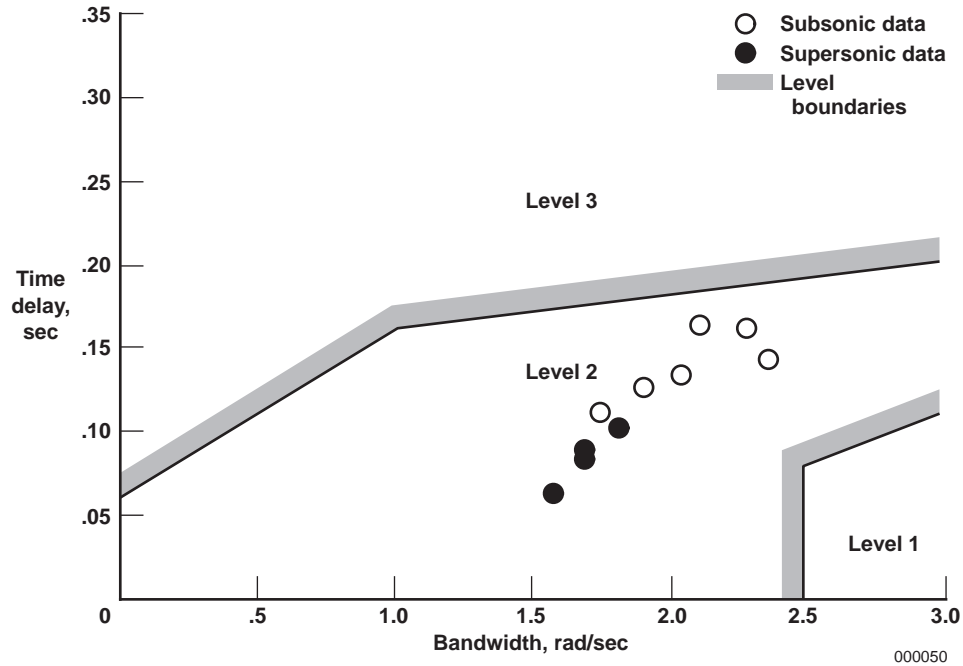
28

Figure 25. Results of bandwidth criterion for category C flight phase.

pilots accepted less bandwidth for a more stable final response (fig. 10). In this sense, the pilot comments are consistent with the category C bandwidth criterion.

This observation also was made for supersonic flight using SR-71 data and an estimate of YF-12 data in reference 8. Figure 26 shows data from this reference overplotted with the supersonic Tu-144LL data and category C requirements. Cooper-Harper ratings of YF-12 and SR-71 maneuvers such as level turns and altitude changes are overplotted near the data. The Tu-144LL data fall in the midst of the SR-71 and YF-12 data, and excellent agreement with the category C criteria is observed.

Reference 11 establishes another set of requirements for terminal area flying for the bandwidth criterion. Figure 27 shows a comparison of the Tu-144LL data with these requirements. Overplotted are the same supersonic YF-12 and SR-71 data as in figure 26. From the data here, the requirements do not appear to be stringent enough for both subsonic and supersonic maneuvering.

Figure 28 shows the gain- and phase-limited bandwidth frequencies as a function of Mach number. From the data, the bandwidth frequencies are observed to be primarily determined by the $-135°$ phase margin criteria. As Mach number increases, the bandwidth frequency slightly reduces from approximately 2.25 rad/sec to approximately 1.75 rad/sec. Intuitively, one might expect the bandwidth to increase as Mach number supersonically increases, because as $1/T_{\theta_2}$ is reduced, more lead is introduced into the phase curve in the $-135°$ phase region. The reason this bandwidth increase may not occur is that the short-period frequency is being reduced (fig. 21). As the short-period frequency is reduced, phase loss occurs at a lower frequency. Thus, the effects of the short-period frequency and $1/T_{\theta_2}$ somewhat offset each other.
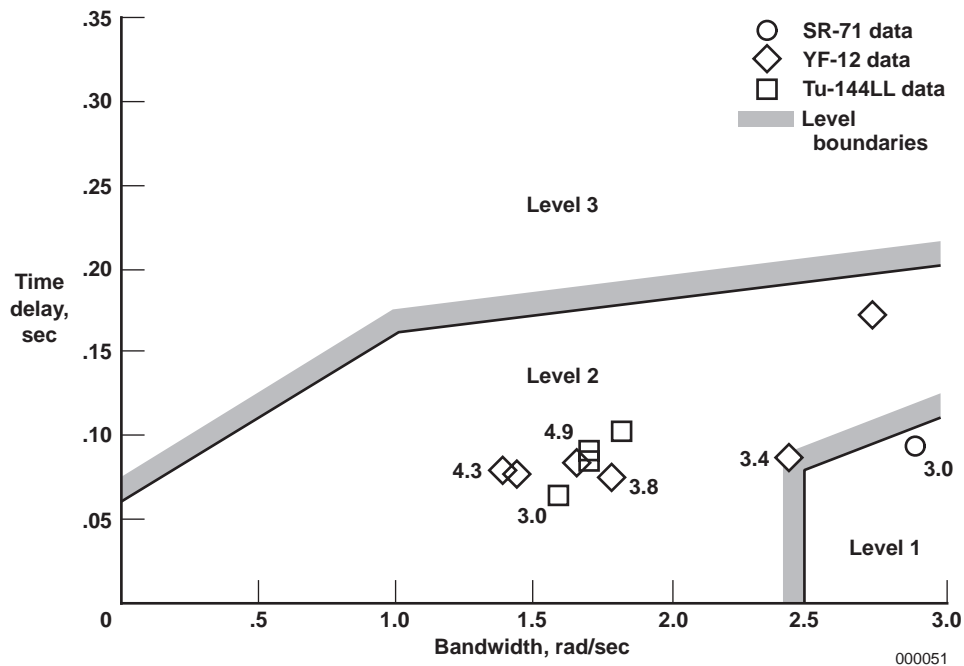
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Figure 26. Results of bandwidth criterion for category C flight phase using supersonic data from Tu-144, YF-12, and SR-71 aircraft.
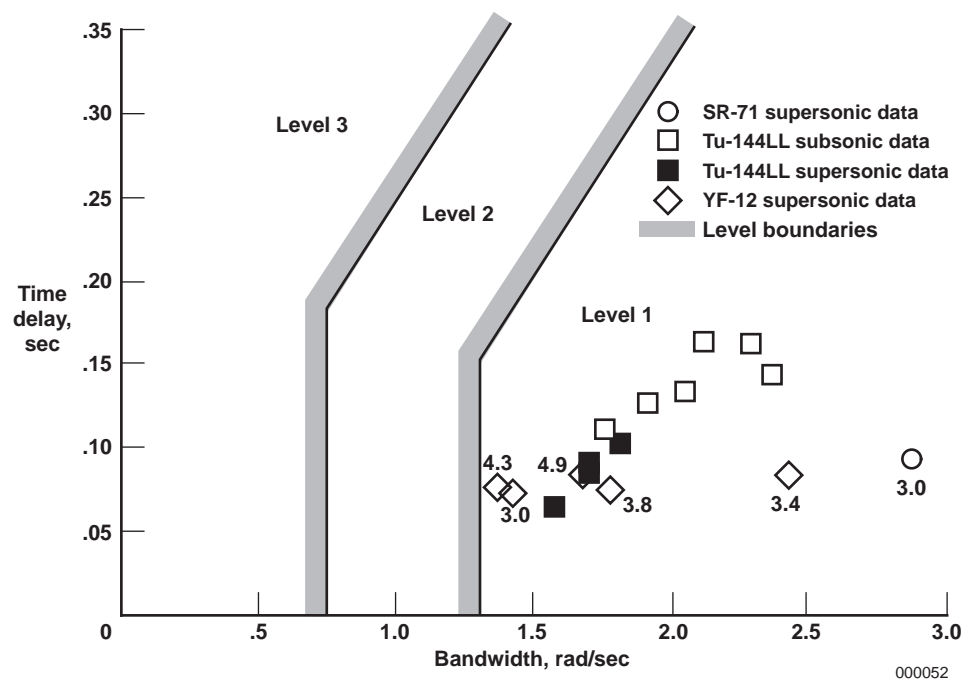

Figure 27. Results of bandwidth criterion for terminal area flight phase requirements from reference 11 for Tu-144, YF-12, and SR-71 aircraft.
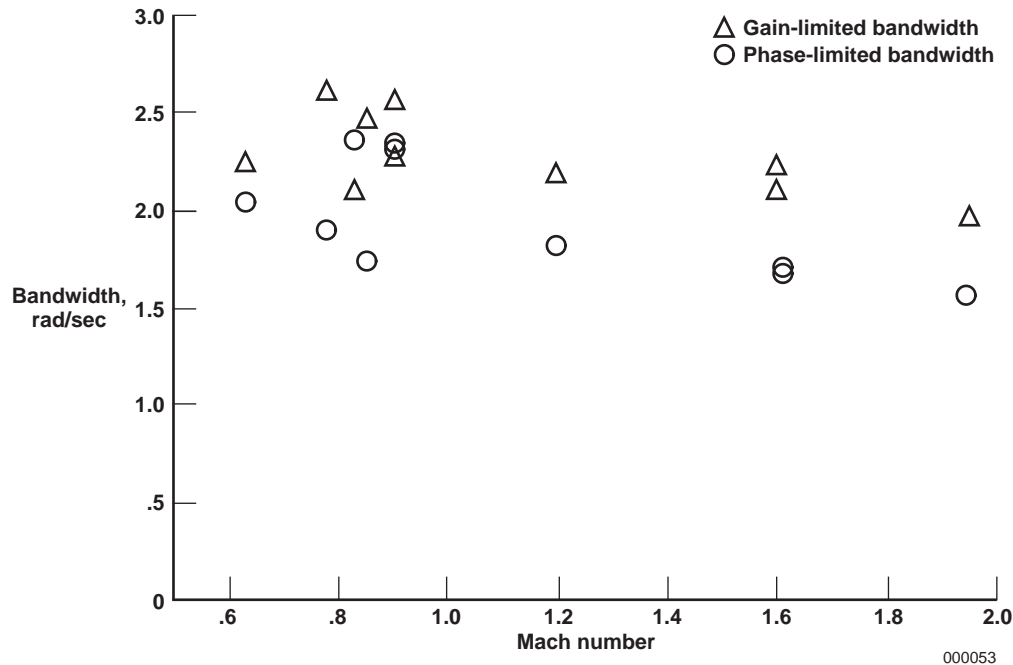
Figure 28. Gain- and phase-limited bandwidth frequency estimates as a function of Mach number.

In the discussion on the Neal-Smith criterion, the shelf-like amplitude (caused by the reduction of $1/T_{\theta_2}$) produced a large effect in the analysis. In the discussion here on the bandwidth and CAP criteria, little effect is noticed. Although the bandwidth criterion does not always accurately predict handling qualities with large, shelf-like amplitude frequency responses, the existence of the shelf has been noticed to cause a degradation in handling qualities because of the fact that small changes in pilot gain can cause rapid deterioration of phase.

Figure 29 shows phase delay estimates as a function of Mach number. Overplotted on figure 29 are the time delay estimates from the low-order equivalent system approach. As Mach number increases, the phase delay estimate from the bandwidth criteria technique reduces from approximately 0.15 sec subsonically to 0.07 sec supersonically, whereas the parameter-estimated technique estimate reduces from 0.15 sec to 0.10 sec. Reference 4 has shown that parameter-estimated time delay and the bandwidth delay correlate well. For two data points each at Mach 0.9, Mach 1.6, and Mach 2.0, approximately 30–40 msec of difference is observed between the estimates. Although 0.10 sec is the official level-1 limit for time delay, the military standard has stated that for Class III airplanes, the real limit is certainly greater, possibly as much as 0.25 sec. Given that all of the data are lower than the relaxed value of the time delay limit, the difference between the estimates may not be meaningful.

Although the pitch bandwidth criterion supplies insight on pilot control of pitch attitude, the resulting flightpath control is not addressed. A criterion to address flightpath control was developed specifically for the terminal flight phase (ref. 7). Given the apparent applicability of category C flight phase to the previous analysis for up-and-away flight, the criterion is applied here as well. The criterion relates the pitch-attitude and flightpath consonance using the pitch-attitude bandwidth as calculated above and the flightpath bandwidth, estimated as the frequency where 45° of phase margin exists in the flightpath–to–column deflection frequency response. For this analysis, the flightpath–to–column deflection frequency response is approximated with the integral of normal acceleration–to–column deflection frequency response.
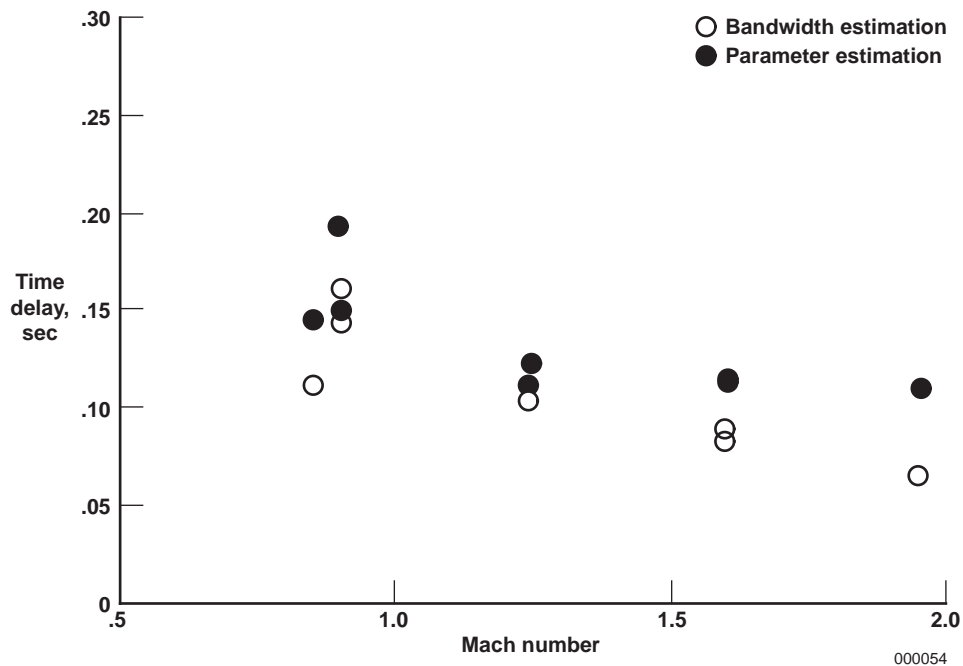
Figure 29. Parameter-estimated and bandwidth-estimated time delay as a function of Mach number.

Figure 30 shows the results and requirements for level 1 and level 2 defined in reference 11. Upper limits of the criterion establish the minimum lag between pitch-attitude response and flightpath response, whereas lower limits establish the maximum tolerable lag. In this sense, the criterion is similar to $\omega_{sp} * T_{\theta_2}$, which represents the amount of lag between pitch-attitude and flightpath response at the short-period frequency. The Tu-144LL data (fig. 30) indicate that subsonic control of flightpath has level-2 characteristics in the region of sluggish flightpath response, but is near the boundary with level 1. Comments from pilot B indicate that leveling off and capturing the target altitude at a speed of Mach 0.9 was easy. Because the subsonic data shown in figure 30 is not far from the boundary of level 1 and level 2, these comments could be considered not to be contradictory.

For supersonic flightpath control, the data indicate characteristics of level 1, but are near the level-2 boundary where the flightpath response begins to follow too quickly after the pitch-attitude response. Pilot B also commented that maintaining altitude in a level turn at a speed of Mach 2.0 was also easy. These comments appear consistent with the analysis, but a previous section of this report has observed that flightpath control during the turns may be more appropriately considered as a category B task, not the category C for which the criterion was established.

A precise up-and-away maneuver was flown in which tight flightpath control was attempted during the climb to Mach-2.0 cruise flight. In this maneuver, pilot B noted that vertical speed control was difficult. The pilot perceived a lag between pitch-attitude and flightpath response. This comment could indicate that flightpath responses were too sluggish, but this comment does not correlate with the high values of flightpath bandwidth observed in figure 30 for supersonic data. Also note that the values for
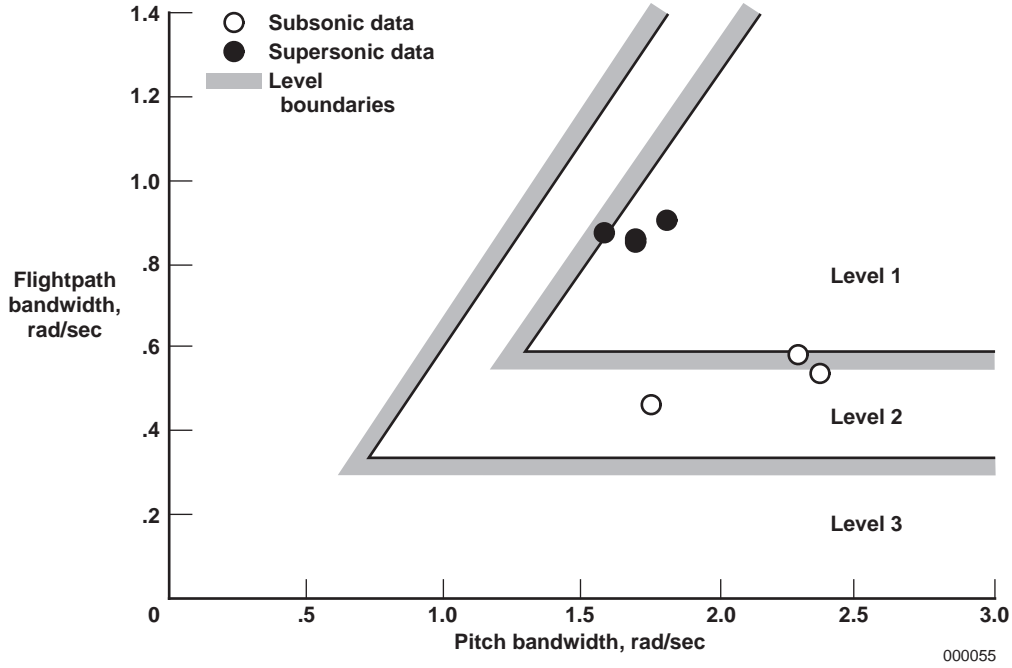
Figure 30. Pitch-attitude bandwidth as a function of flightpath bandwidth.

$\omega_{sp}*T_{\theta_2}$ and flightpath bandwidth contradict each other. Whereas the flightpath bandwidth indicates that flightpath delay decreases from subsonic to supersonic, $\omega_{sp}*T_{\theta_2}$ indicates that the delay is increasing.

Understanding why flightpath bandwidth increases for supersonic flight is interesting. Intuitively, one would expect the lag to increase for supersonic flight because $1/T_{\theta_2}$, which relates pitch-attitude and flightpath response, decreases with Mach number. Indeed, the pilot comments during the climb would tend to support the effect of the decreased $1/T_{\theta_2}$. Supersonic SR-71 and estimated YF-12 data were applied against this criteria in reference 8 and are overplotted with the Tu-144LL data in figure 31. A similar trend of high flightpath bandwidth for supersonic data with the SR-71 and YF-12 aircraft is noted.

Figure 32 shows one possible explanation for these higher flightpath bandwidth estimates for supersonic flight in the calculation of the flightpath bandwidth for Mach 0.9 and Mach 2.0. The short-period damping is smaller (0.3) for the Mach-2.0 case, which causes the phase curve to drop off less quickly than the subsonic phase curve in the frequency range in which the bandwidth is calculated. The resulting flightpath bandwidth estimate for supersonic flight then tends to be higher than for subsonic flight.
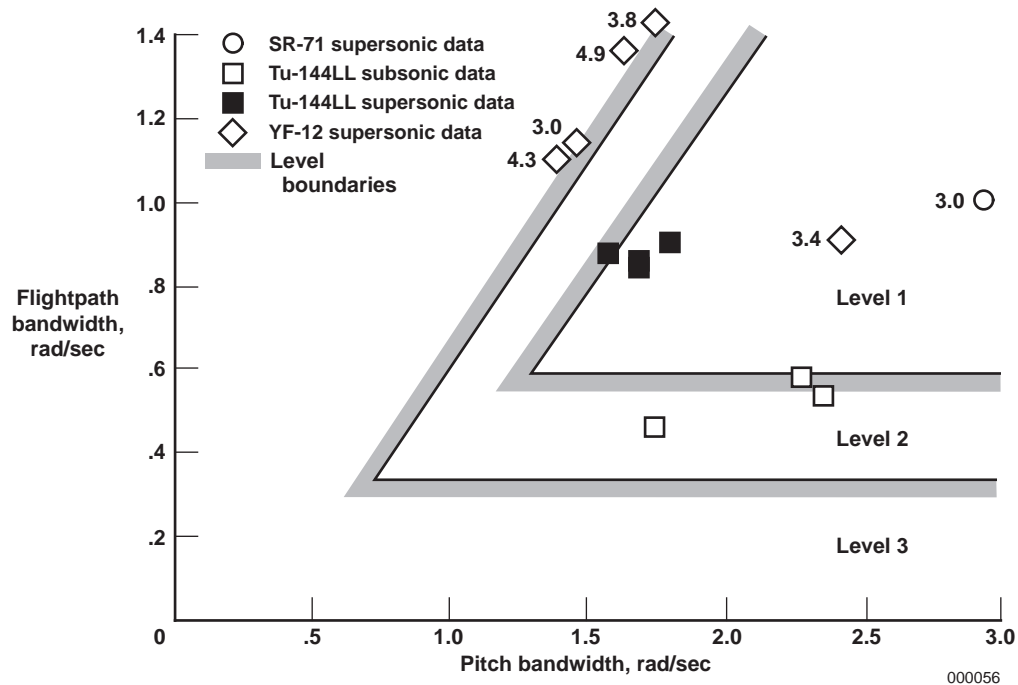
Figure 31. Pitch-attitude bandwidth as a function of flightpath bandwidth for Tu-144, YF-12, and SR-71 data.
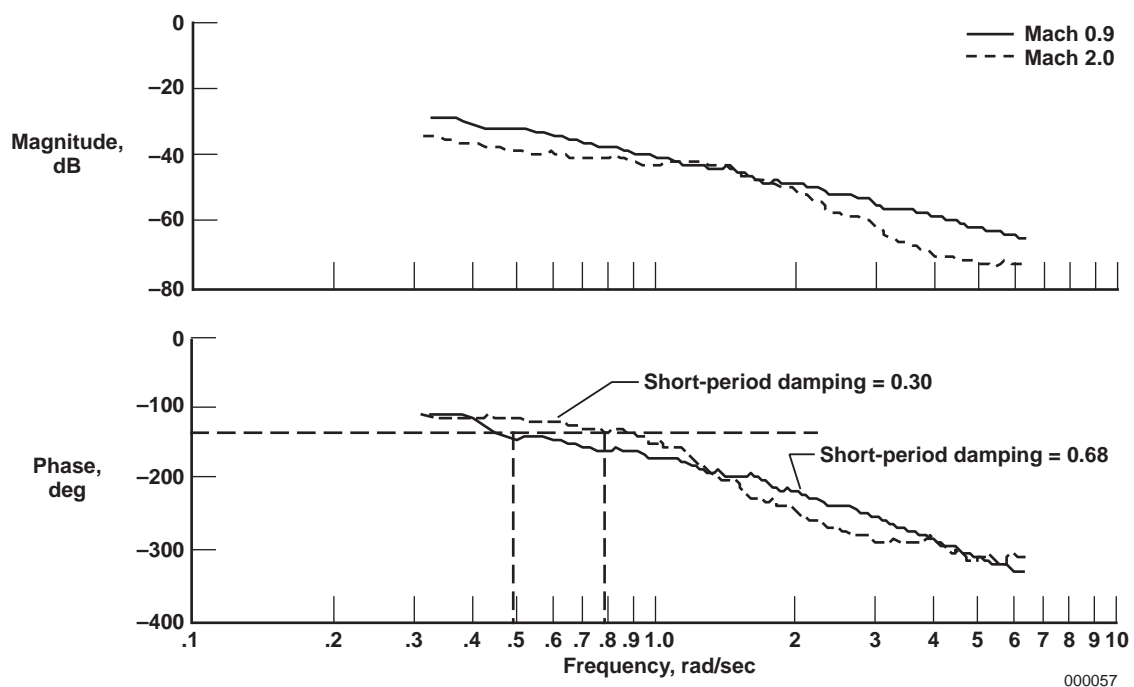

Figure 32. Comparison of the integral of normal acceleration–to–column frequency responses for subsonic and supersonic cruise conditions.

CONCLUSIONS

Comparison of Tu-144LL up-and-away quantitative data and qualitative pilot comments and ratings were compared to the following longitudinal flying qualities criteria: Neal-Smith, short-period damping, time delay, control anticipation parameter (CAP), phase delay ($\omega_{sp} * T_{\theta_2}$), pitch bandwidth as a function of time delay, and flightpath as a function of pitch bandwidth. Insufficient data were collected to be statistically significant, but the program provided the opportunity to collect data from this unique class of aircraft to compare with other test programs. Comparing appropriate YF-12, XB-70, and SR-71 pilot ratings to the Tu-144LL data aided in the interpretation of Tu-144LL data and helped gain insight into the application of the various criteria. The results of the study are listed below.

1. The Neal-Smith criterion with a time delay of 0.25 sec correlates best with pilot comments when using a 2.5-rad/sec bandwidth for subsonic flight and a 1.5-rad/sec bandwidth for supersonic flight. Both these bandwidths are identified in the flying qualities military standard as "category C" type requirements. Results using vertical speed or flightpath frequency response data in the Neal-Smith analysis show potential improvement for supersonic handling qualities, which is consistent with previous SR-71 data.

2. The applicability of the Neal-Smith criterion, and possibly others, can be affected by the data displayed to the pilot. A good display of the right information can improve aircraft handling qualities, even if the criterion does not predict good characteristics, which was true for the SR-71 aircraft. Applying the Neal-Smith analysis with the pitch-attitude frequency response results in the criterion predicting poor handling qualities. However, pilot evaluations of the airplane show that using an inertially derived, vertical speed feedback as the primary pilot cue (not pitch attitude as the Neal-Smith analysis requires) results in favorable pilot comments and ratings.

3. Normally, the flying qualities design of aircraft use category C requirements only in the terminal phase of flight. However, for large, supersonic aircraft, up-and-away category C tasks exist that require precision flightpath. This requirement is shown through correlation of the CAP, pitch bandwidth as a function of time delay, and the Neal-Smith criterion with category C requirements. The flying qualities design to category C requirements using these criteria for these type of aircraft would be applicable.

4. The CAP correlates with pilot comments better than $\omega_{sp} * T_{\theta_2}$ for the Tu-144LL and XB-70 data. Pilot comments indicating flightpath overcontrol and pitch-attitude sensitivity match trends observed in the CAP data, whereas $\omega_{sp} * T_{\theta_2}$ data predict no adverse comments. Pilot comments on the ease of flightpath control at the cruise condition correlate with CAP data for the category B requirement.

5. The criterion on pitch bandwidth as a function of time delay correlates well with pilot comments regarding pitch-attitude sensitivity. The criterion on flightpath bandwidth does not correlate well because of high values of flightpath bandwidth estimated for supersonic flight.

6. As Mach number increases, the following characteristics are observed in the criteria:

   • The Neal-Smith criterion shows an increase in pilot lag and resonant peak. The pilot lag is attributed to the increase in the high-frequency pitch-attitude time constant (T_{θ_2}) typical of increasing Mach number.

   • The value of $\omega_{sp} * T_{\theta_2}$ increases, also because of the decrease in $1/T_{\theta_2}$.

- The value of flightpath bandwidth significantly increases as a result of the decrease in short-period damping typical of conventionally designed aircraft with rate dampers.

- The low-order equivalent system–estimated time delay and the time delay calculated in the pitch bandwidth criterion decrease, although some discrepancy was observed between the two values.

- The CAP slightly decreases as the decrease in $1/T_{\theta_2}$ is offset by the increase in velocity.

- The values of pitch bandwidth are not significantly affected by the decrease in $1/T_{\theta_2}$ and corresponding shelf-like characteristic observed in the magnitude of the pitch-attitude frequency response.

7. The flying qualities implications of decoupled pitch-attitude and flightpath responses occurring for high-speed flight where $1/T_{\theta_2}$ is small may be mitigated by requiring the pilot to close the loop on flightpath or vertical speed instead of pitch attitude. Improvement in SR-71 and Tu-144LL handling qualities at supersonic cruise were observed through comparison of Neal-Smith analysis of flightpath and pitch-attitude frequency responses.

Dryden Flight Research Center
National Aeronautics and Space Administration
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APPENDIX
DESCRIPTION OF MANEUVERS

Maneuvers flown in the evaluation program are detailed below. Modifications to target values were required for some of the maneuvers based on flight condition.

Deceleration and Acceleration

1. Reduce throttle from trim position to approximately 20°.
2. Decelerate and capture an airspeed 70 km/hr less than trim.
3. Advance throttle to military power setting.
4. Accelerate and recapture original airspeed.

Pitch-Attitude Capture

1. From trim attitude, pull column back to capture a 3° pitch-attitude increment.
2. Push column forward to capture original trim attitude.
3. From trim attitude, push column forward to capture a –2° pitch-attitude increment.
4. Pull column back to capture original trim attitude.
5. Throughout steps 1–4, keep normal acceleration between 0.8 and 1.2 g.

Bank-Angle Capture

1. From steady level flight, apply right wheel to capture a 30° bank angle.
2. Apply left wheel to capture level flight.
3. From steady level flight, apply left wheel to capture a –30° bank angle.
4. Apply right wheel to capture level flight.

Heading Captures

1. From steady level flight, apply right wheel to capture a 30° bank angle.
2. Maintain bank angle and capture 20° heading increment.
3. Apply left wheel to capture a –30° bank angle.
4. Maintain bank angle and capture original heading.
5. Repeat steps 1–4 in opposite direction.

Steady-Heading Sideslips

1. From steady level flight, apply a series of rudder deflections: 2°, 4°, 6°, and 7.5°.

2. Apply appropriate wheel deflection to maintain constant heading, stabilizing for 5 sec on each rudder deflection.

3. Repeat steps 1–2 in opposite direction.

Simulated Engine Failure

1. From steady level flight, retard throttle number 1 to idle.

2. Wait 5 sec and then stabilize transient, maintaining a bank angle less than ±5°.

3. Advance three remaining throttles to capture original airspeed.

4. Perform heading capture maneuver.

5. Recover by slowly advancing number 1 throttle and reestablish original flight condition.

Slow Flight

1. From steady level flight, pull column back and establish a (2 km/hr)/sec deceleration.

2. At minimum airspeed or warning, stop deceleration and hold condition for 3 sec.

3. Recover by pushing column forward and establishing original flight condition.

4. From steady level flight, establish a 30° bank turn.

5. Pull column back and establish a (2 km/hr)/sec deceleration.

6. At 10 km/hr greater than the minimum airspeed or warning indication, stop deceleration and hold condition for 3 sec.

7. Recover by pushing column forward, rolling wings level, and establishing original flight condition.

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13. ABSTRACT (Maximum 200 words)

Four flights have been conducted using the Tu-144LL supersonic transport aircraft with the dedicated objective of collecting quantitative data and qualitative pilot comments. These data are compared with the following longitudinal flying qualities criteria: Neal-Smith, short-period damping, time delay, control anticipation parameter, phase delay ($\omega_{sp} * T_{\theta_2}$), pitch bandwidth as a function of time delay, and flightpath as a function of pitch bandwidth. Determining the applicability of these criteria and gaining insight into the flying qualities of a large, supersonic aircraft are attempted. Where appropriate, YF-12, XB-70, and SR-71 pilot ratings are compared with the Tu-144LL results to aid in the interpretation of the Tu-144LL data and to gain insight into the application of criteria. The data show that approach and landing requirements appear to be applicable to the precision flightpath control required for up-and-away flight of large, supersonic aircraft. The Neal-Smith, control anticipation parameter, and pitch-bandwidth criteria tend to correlate with the pilot comments better than the phase delay criterion, $\omega_{sp} * T_{\theta_2}$. The data indicate that the detrimental flying qualities implication of decoupled pitch-attitude and flightpath responses occurring for high-speed flight may be mitigated by requiring the pilot to close the loop on flightpath or vertical speed.

14. SUBJECT TERMS

Bandwidth criterion, Control anticipation criterion, Flying qualities, Neal-Smith criterion; Short period criteria, SR-71 aircraft, Supersonic flying qualities, TU-144 aircraft, XB-70 aircraft

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